MODELING PRESENT AND FUTURE ABOVEGROUND BIOMASS OF EVERGREEN BROADLEAF FORESTS IN VIETNAM

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ABSTRACT

Forest reforestation and degradation have both occured over the past five decades in Vietnam. To cope with this problem, the Vietnamese government has established plans and set up strategies to reduce deforestation and forest degradation. It also launched national support for the conservation and sustainable management of forests, as well as enhancement of forest carbon stocks in developing countries (REDD+) programs. A limited number of studies have attempted to establish a database of aboveground biomass of evergreen broadleaf forests in Vietnam, as well as growth models such as height versus diameter at breast height (H-D) models, basal area (G) increment models, and above ground biomass (AGB) increment models. In addition, the information describing the relationships between environmental indicators and tree species distributions was also insufficient, leading to potential failure of reforestation and rehabilitation projects.

This study examined the correlation between environmental indicators and tree species distributions. It also sought to develop H-D models based on the outcomes of grouping tree species into different groups, and model the relationship between G and AGB increments with other environment factors and stand characteristics.

The study utilized data collected from Forest Inventory and Planning Insititution (FIPI) and valiation data from Vietnamese Academy of Forest Sciences (VAFS). It then employed ordination analysis to analyse the correlation between tree species groups and environmental factors. In addition, previous H-D functions applied in past research on tropical forests were used to develop H-D models for this particular study. Validation procedures were used to compare selected H-D models with other H-D

models applied in the same forest types. Lastly, a decision tree approach was adopted to select the climatic, soil, and stand variables that were most likely to be useful for the development of G and AGB increment models.

The findings were that there was a correlation between solar radiation, depth to bedrock, clay content, temperature and rainfall with tree species distributions. Nine selected H-D models for nine respective tree species groups were less biased and more precise comprared to two given H-D models in a validation procedure. Finally, both G increment models and AGB increment models were developed, in which these climatic, soil, and stand variables were directly added. The study was intended to contribute valuable data and relevant models for the benefit of forest managers and administrators who could use the results to effectively carry out the process of reforestation, REDD+ projects, and national forest inventories programs at minimal cost in timely and efficient manners.

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LIST OF SYMBOLS AND ACRONYMS

Symbol/Acronym	Description	Unit
AGB	Aboveground biomass	ton/ha
AGBi	Aboveground biomass increment	ton/ha/year
AIC	Akaike information criterion	-
G	Basal area	m^2/ha
G_i	Basal area increment	m^2/ha/year
Brock	Depth to bedrock	cm
Bulk	Bulk density	kg/m^3
CC	Soil organic carbon content	g/kg
Cex	Cation exchange capacity	cmolc/kg
Clay	Clay content	%
CP	Complexity parameter	-
CS	Soil organic carbon stock	tones/ha
DATA1	Modelling data	
DATA2	Validation data for H-D models	-
DATA3	Validation data for G and AGB increment model	-
dbh	Diameter at breast height	cm
Elev	Elevation	m
EPP	Ecological permanent plot (1 x 1 km plot, defined by FIPI)	-
e^x	the base of the natural logarithm	-

GHG	Greenhouse Gas	-
H	Tree height	m
HDF	Heavily disturbed forest	-
IPCC	Intergovernmental Panel on Climate Change	-
KP	Kyoto Protocol	
LDF	Lightly disturbed forest	-
LULUCF	land use, land-use change, and forestry	-
m	Annual mortality rate	-
MAE	Mean absolute percent error	%
MMAS	mean maximum attainable size	-
n	Annual recruitment rate	-
PES	Payment for environmental services	-
pH	Soil pH in KCl	-
PSP	Permanent sample plot	-
Rain	Mean rainfall	mm/year
REDD+	Reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries	-
RSE	Residual standard error	-
S	Bias	%
Sand	Sand content	%
SE	Standard error	-
Silt	Silt content	%

Srad	Solar radiation	kJ m^{-2} day^{-1}
SSE	The sum of squares of the residuals	-
Tb-RDA	Transformation-based Redundancy Analysis	-
Temp	Mean temperature	^{0}C/year
UDF	Undisturbed forest	-
UNFCCC	The United Nation Convention Framework on Climate Change	-
V	Timber volume	m^3/ha
WD	Wood density	g/cm^3

CHAPTER 1

INTRODUCTION

BACKGROUND

Schimper (1893) coined the term "evergreen forest" which is often used interchangeably with "tropical rain forest", mainly referring to those forests in the permanently wet tropics (Schimper, Fisher, Groom, & Balfour, 1903). Tropical rain forests are characterized as "the tall, dense, evergreen forest that forms the natural vegetation cover of the wet tropics, where the climate is always hot; and the dry season is short or absent" (Primack & Corlett, 2005). However, there is significant variation in tropical rain forests from region to region (Whitmore, 1990), caused by ecological and historical factors (Primack & Corlett, 2005).

As of 2016, Vietnam had approximately 10.2 million hectares of natural forests that are mostly evergreen broadleaf forests (Ferrand, 2018). These forests are important in protecting the environment and in providing livelihoods for the local people living in mountainous and remote areas. According to Whitmore's (1990) classification, the forests in Vietnam can be classified into tropical lowland evergreen rain forests, tropical lower montane rain forests, and tropical upper montane rain forests. They are largely distributed at altitudes below 700 m in the North and 1000 m in South Vietnam (Lan, Hong, Hung, Thin, & Chan, 2006), and between 200 m to 1800 m above sea level in the Central Highlands (Hai, Do, Trieu, Sato, & Kozan, 2015). The forests in Vietnam fall under the categories of tropical lowland evergreen rain forests, tropical lower montane rain forests, and tropical upper montane rain forests (Whitmore, 1990). The forests can be typically stratified into the following canopy layers: the emergent, canopy, understory, shrub, and herb layers. Important families in the emergent layer and canopy layer are Dipterocaparceae, Moraceae, Leguminosae, Fagaceae, Lauraceae, Caesalpiniaceae, and Mimosaceae (Lan et al., 2006).

However, for the purposes of forest management, Vietnam's forests are also classified as poor, medium or rich (Meyfroidt & Lambin, 2008). Rich forests have remained undisturbed for at least 60-80 years; secondary forests (medium) are those already well restored, while poor forests are those with young secondary or pioneer species. In addition, Hai et al. (2015) pointed out that the forests can be further categorized into five different standing forest volume (V) classes. These categories include very poor forests ($V \leq 10$ m^3 ha^{-1}), poor forests ($10 < V \leq 100$ m^3 ha^{-1}), medium forests ($100 < V \leq 200$ m^3 ha^{-1}), rich forests ($200 < V \leq 300$ m^3 ha^{-1}), and very rich forests ($V > 300$ m^3 ha^{-1}). Each of these forest categories can also be identified as heavily disturbed forests (HDFs), lightly disturbed forests (LDFs), and undisturbed forests (UDFs) (Ngoc Le et al., 2016).

In the early 20th century, 60% of the land area of Vietnam is covered by forests, but declined to 43% by 1943. Eventually, because of the Vietnam War and agricultural expansion, the total forest area of Vietnam further decreased between 25 to 31% in 1991 – 1993 (Meyfroidt & Lambin, 2008; UN-REDD, 2013). The deforestation rate was at its peak during the 1970s and 1980s, at an average rate of 1.4% per year. Between 1980 and 2005, the proportion of undisturbed forests, especially broadleaf forests that had previously covered around 60% to 70% of natural forests, had decreased dramatically. This means that heavily disturbed forests have become a large proportion of new and young forests, approximately 60% of the total forest cover by 2005 (Meyfroidt & Lambin, 2008). The total forest area of Vietnam increased from 9.2 million ha in 1992 to 13.4 million ha in 2009 – equivalent to 39.7% of the total land area of the country (UN-REDD, 2013), but with a decline of forest quality (Pham, Moeliono, Nguyen, Nguyen, & Vu, 2012).

The main reasons behind the recent deforestation and forest degradation in Vietnam have changed, which significantly differ from those in the early 20th century. Pham et al. (2012) summarized two key drivers of deforestation and forest degradation in Vietnam, including direct and indirect drivers. During recent years, the main direct causes included: 1) land conversion for agricultural cultivation; 2) land use change for infrastructure development; 3) unsustainable logging including both legal and illegal logging; and 4) forest fires including natural reasons and human disturbances. The main indirect causes of deforestation and forest degradation included the increasing demand for forest products and agricultural land, the economic development and growing wood demand for the pulp and paper industry, construction and fuel. However, beneath these direct and indirect causes are critical issues such as ineffective development policies, weak governance at all levels, and the lack of financial resources for forest protection that paved the way for unsustainable logging and unplanned conversion (Pham et al., 2012).

To increase forest cover and quality, the Central Communist Party strategy for Industrialization and Modernization, 2000 – 2020, introduced five forestry objectives, which were successfully completed by 2010. These objectives include:

1) Increasing the forest cover to 43 % of Vietnam's territory,

2) Completing the forestland allocation to households and other entities,

3) Promoting forest-based livelihoods,

4) Protecting 10 million ha of natural forests through a household management approach, and

5) Accelerating the development of forest plantations (UN-REDD, 2013).

To realize these forestry objectives there must be an implementation of emissions reduction from deforestation and forest degradation, national support in the conservation and sustainable management of forests, as well as the enhancement of forest carbon stocks in developing countries (REDD+) programs in Vietnam. These will enhance and protect natural forests in general, and evergreen broadleaf forests in particular, which should result in the realization of the country's forestry objectives.

The urgency to accomplish these objectives is highlighted by the fact that Vietnam is one of the first countries to sign and ratify both the United Nation Convention Framework on Climate Change (UNFCCC) and the Kyoto Protocol (KP). According to the standards of UNFCCC and KP, Vietnam is predicted to be one of the five countries most adversely affected by climate change (ISPNR, 2009). In addition, these also contributed to the tranparency in the development of national communications, biennial reports and biennial updated reports of Vietnam, which are supported by country-specific data and followed the modalities, procedures and guidelines introduced by UNFCCC (UN, 2015).

Because of this, the government has since displayed commitment in its efforts to the United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (UN-REDD) Vietnam Program, as Vietnam's initiativeness to take action to conserve and enhance sinks and reservoirs of greenhouse gases (UN, 2015), to contribute to the 2020 target for agricultural and rural development emission reductions (UN-REDD, 2013).

The Vietnamese government has made efforts to promote restoration projects in order to increase its forest cover (Jong, 2006; Millet, Tran, Vien Ngoc, Tran Thi, & Prat, 2013). As a result, Vietnam's forest cover in 2013 significantly increased at similar rates to those experienced in 1943 (Cochard, Ngo, Waeber, & Kull, 2017). However, the country has confronted various challenges such as selecting the tree species to be used in forest enrichment planting in degraded natural forests. Nghia (2007) pointed out that there were four main challenges confronting foresters and forest managers in tree species selection for restoration purposes. These challenges relate to scientific knowledge, awareness, technology, and socio-economic aspects.

Among these challenges, scientific knowledge is considered to be the most important factors since it relates to the relationship between the species and local soil types, climate, nutrition and light requirements, as well as interactions between species within multi-species associations (Nghia, 2007). However, inter-relationships between tree species associations and environmental factors are complex (Y. M. Zhang, Chen, & Pan, 2005), yet studies on this topic in Vietnam are very limited. At present, multivariate analysis is a good alternative to explore the joint relationships between tree species diversity and environmental variables (F. C. James & McCulloch, 1990).

The estimation of aboveground biomass is critical for the implementation of payment for environmental services (PES) and REDD+ (Jeyanny et al., 2014; Ngo et al., 2013). Large areas of tropical forests have disappeared in the past few decades, such as those in the Amazonia decreasing at an estimated rate of 2 million ha year^{-1} (I. F. Brown et al., 1995). Since more forests are under threat of deforestation and forest degradation, the REDD+ mechanism has emerged to maintain both carbon pools and biodiversity. Such initiatives may also contribute to social and economic development (Gibbs, Brown, Niles, & Foley, 2007; Hai et al., 2015; Ngo et al., 2013). As such, aboveground biomass estimation is critical for sustainable forest management and for the REDD+ report, as well as for the transparency framework under the Paris Agreement.

Vietnam has limited country-specific data that urgently needs to be expanded and complemented to develop the baseline scenarios required by the REDD+ projects. Pham et al. (2012) stated that emission factors used in Vietnam are mainly default values introduced by the Intergovernmental Panel on Climate Change (IPCC). These factors are generalized across different types of landscapes and forests, which may lead to high uncertainty in the development of emissions baseline scenarios. Researchers in Vietnam are mainly focused on the development of emission factors and biomass equations for forest plantations. However, there is still a limited number of studies addressing these issues for natural forests.

OBJECTIVES

The main objective for this study was to assess and model AGB increment for evergreen broadleaf forests in Vietnam, and specifically,

1. To explore effects of environmental factors on tree species composition and distribution of broadleaf forests.
2. To develop tree height - diameter models for different species functional groups.
3. To develop AGB and G increment models at the stand level.

RESEARCH QUESTIONS

In line with these objectives, this study has the following research questions:

1. How do environmental variables affect tree species composition and distribution of each key tree species group?
2. How biased and precise are models created to project tree height, AGB and G increment?
3. Do initial AGB, species richness and environmental factors contribute to explain the stand-level AGB increment?

HYPOTHESES

In answering the questions above, this study proposes the following:

- The first question leads to the hypothesis that environmental variables and tree species composition and distribution are strongly related.
- The second question leads to the hypothesis that models of H-D, G and AGB increment are relatively unbiased and tolerably precise.

- The last question leads to the hypothesis that the AGB increment is driven by the initial AGB, species richness and environmental variables.

THESIS STRUCTURE

This thesis covers different aspects of aboveground biomass of evergreen broadleaf forests in Vietnam. It includes the effects of environmental factors on tree species composition and distribution of main tree species groups, development of H-D models for each group using different functional forms, and fitting AGB and G increment models that may contribute to sustainable forest management and achieving climate change goals.

In chapter 2, there are two key points, including tree species aggregation and H-D modelling development. In regard to tree species grouping, agglomerative hierarchical clustering, optimal univariate clustering and k-means clustering algorithms were used to select the most appropriate method for grouping species. Tb-RDA was used to analyse the correlation between tree species and environmental factors, and to explore distribution patterns of three main tree species groups. These groups included all intolerant tree species that comprised more than 72% of total tree data approximately, which were widely distributed throughout the country.

Chapter 3 describes the development of H-D models for each tree species group. In addition, H-D models were also developed for some specific tree species that exhibited abnormal growth patterns. Several H-D functional forms were fitted to the data of each tree species group based on the statistics of precision and bias. This study found that the Weibull and conditioned Weibull forms showed the best fits to the data of each group. Finally, a validation procedure and a comparison with other regional and national models were used to assess the precision and bias of the selected H-D equations.

Chapter 4 reports the development of AGB increment and G increment models for future projection at the stand level. AGB of the forest was calculated for each ecoregion and forest types that are under the definition of the government. A linear form was used to explore the relationship between AGB increment and G increment and environmental variables and stand variables. A decision tree approach was used to reduce the number of independent variables. Graphical analyses were also used to explore any side effects of individual independent variables in selected AGB and G increment models. In addition, an independent dataset of 34 1-ha permanent sample plots was used to validate selected models. Finally, selected stand parameters and environmental factors was used to develop stand-level AGB and G increment models.

Chapter 5 summarises the key findings of the study with their implications for forest management and future applications.

CHAPTER 2

THE EFFECTS OF ENVIROMENTAL FACTORS ON TREE SPECIES DISTRIBUTION OF BROADLEAF FORESTS IN VIETNAM

INTRODUCTION

Vietnam is known for being one of the most biologically-diverse nations in the world (The Ministry of Environment and Natural Resources of Vietnam, 2005). Thin (1997) pointed out that there are approximately 15,000 tree species belonging to 378 families and 2524 genera in forest ecosystems in Vietnam. Evergreen broadleaf forests in Vietnam normally include more than 70 species per hectare (H. T. T. Do, Grant, Trinh, Zimmer, & Nichols, 2017) varying in life spans and ecological growth characteristics. Thus, species grouping is a key step in model development (Alder & Silva, 2000).

Tree species groupings can be categorised into three types: ecological subjective, ecological data-driven, and groupings based on dynamic processes (Gourlet-Fleury *et al.*, 2005). The first type is dependent on characteristics that are easy for foresters to assess over short periods of time (Swaine & Whitmore, 1988) such as physiological and morphological traits (Gourlet-Fleury *et al.*, 2005), an example of which are the groups of pioneer and non-pioneer species. This approach requires well-documented data and relies on empirical knowledge from field observation (Gourlet-Fleury *et al.*, 2005). The approach is simple and applicable to all tropical rain forests (Swaine & Whitmore, 1988). However, a disadvantage of this approach is that there are not necessarily relationships between biological characteristics and subjective groups, with species within a group differing in growth, mortality and recruitment (Gourlet-Fleury *et al.*, 2005).

As the second grouping strategy, the ecological data-driven groups can be based on the following:

1) dynamic characters such as diameter increment, mortality rate and recruitment rate (Picard, Magnussen, Banak, Namkosserena, & Yalibanda, 2010);

2) morphological characters such as maximum attainable tree height (Köhler, Ditzer, & Huth, 2000; Masripatin, 1998); commercial and non-commercial categories (Ong, Kleine, & Hutan, 1995); taxonomic classification (Phillips, Yasman, Brash, & van Gardingen, 2002); or

3) a mixed approach combining both (Masripatin, 1998; Ong et al., 1995; Whitmore, 1990).

The main disadvantage of this grouping strategy is that growth, mortality and recruitment sub-models are parts of general forest dynamic models, which may lead to inadequacy for modelling growth due to differing growth characteristics of tropical species (Phillips *et al.*, 2002).

For the third grouping strategy, dynamic process groups are mainly dependent on one type of dynamic trait (Gourlet-Fleury & Houllier, 2000; Ong *et al.*, 1995). For instance, growth groups are dependent on diameter increments, while mortality groups are associated with mortality rates. The dynamic process method is used to build groups by relying on theoretical models. In contrast to the other strategies previously mentioned, groups of dynamic processes are derived using a model; however, the ecological meaning of the groups may be hindered (Gourlet-Fleury *et al.*, 2005). This approach also requires data that would be collected from permanent sample plots at different points in time, which are not usually available for tropical forests. These classification methods have been used in a number of other studies to group species for different modelling purposes (Adame, Brandeis, & Uriarte, 2014; Alder & Silva, 2000; Gourlet-Fleury et al., 2005; Köhler & Huth, 1998; Phillips et al., 2002; Vanclay, 1991).

In recent years, classification by functional group has been widely used in growth modelling studies. Kariuki, Rolfe, Smith, Vanclay, and Kooyman (2006) used regeneration strategy and shade tolerance to group 117 subtropical rainforest tree species of north-eastern NSW (Australia) into five functional groups. Similarly, Adame et al. (2014) and Masripatin (1998) used regeneration strategy and the average maximum tree height as criteria for grouping species for studies regarding diameter growth performance and growth modelling. Masripatin (1998) argued that using tree functional groups may improve model efficiency because it becomes impractical to develop one model for each species.

For more than a century, researchers in ecology have tried to explore factors controlling tree species distributions and species composition of stands (Chahouki MAZ, 2008). Recently, the effects of environmental elements on tree species communities have become the core subject of a large number of ecological studies (Chahouki MAZ, 2008; De Souza *et al.*, 2007; Tardella, Postiglione, Vitanzi, & Catorci, 2017; Y. M. Zhang *et al.*, 2005). Climate, topography and soil have been considered as key factors that influence tree species composition and abundance (Nizam, Jeffri, & Latiff, 2013; W. Peng *et al.*, 2012; Tardella *et al.*, 2017). However, the impact of these factors on tree species communities vary. For example, a close connection was detected between soil factors and vegetation distribution in a large number of studies *(Baillie et al.*, 1987; Nizam *et al.*, 2013; Pyke, Condit, Aguilar, & Lao, 2001), while other ecologists also pointed to the relationship between species community and topography (Davies & Becker, 1996; S., 2010; Tardella *et al.*, 2017; Webb & Peart, 2000).

Whitmore (1998) argues that tree species composition in tropical forests significantly varies from site to site mostly due to variation in topography, habitat and disturbance. Evergreen broadleaf forest (EBF) is widely distributed from north to south ($8^{0}34'$ to $23^{0}23'$N) and from east to west ($102^{0}09'$ to $109^{0}24'$E) in Vietnam. EBF can be found along the whole coastline of Vietnam. This leads to differences in seasonal patterns, rainfall and temperature regimes, and great variation in topography among EBF (Vu Tan Phuong, 2010). The forest comprises a large percentage, covering approximately 29% of the country (Ferrand, 2018; Hai *et al.*, 2015) and plays a key role in preserving biodiversity and in enhancing resilience to climate change.

However, studies of relationships between tree communities and environmental factors are very limited. There are only a few studies and mostly at a reduced spatial scale. Hoa Hong Dao and Hölscher (2015) found a relationship between some red-listed tree species and the presence of footpaths, canopy and basal area in the Ta Xua Nature Reverse in north-western Vietnam. In particular, canonical correspondence analysis in this study indicated a negative relationship between footpaths and these red-list species, which suggested a reduction of human activities. Van Nguyen, Mitloehner, Bich, and Do (2015) assessed 13 environmental variables to explore distributions of tree species in tropical limestone forests in Ben En National Park, Vietnam. They concluded that there was a close relationship between environmental factors and abundances and distributions of tree species. To date, however, the relationship between broadleaf forest tree species and environmental variables at a large spatial scale covering all Vietnam has not been analysed.

In ecology, Pearson correlation analysis, Spearman correlation and Kendall correlation analysis could be applied to measure the strength of association and the direction of relationships. However, these approaches are only describe relationships between two variables at a time. Ordination is a very effective technique to describe relationships between species composition patterns and the underlying environmental gradients in a multivariate fashion. The technique is a multivariate analysis used to explore continuous patterns in multiple dimension data, such as that of species abundance and environmental variables. It can provide imaginable, interpretable and printable dimensions from reductions of multidimensional information held in large datasets (Zelený, 2018). It can be used either to describe vegetative community characteristics or to explore and test changes in species composition by environmental variables.

There are two types of ordination: unconstrained ordination (or indirect gradient analysis), and constrained (or canonical) ordination. The main difference between the two is whether or not environmental variables are included in the ordination algorithm. The axes of unconstrained ordination are not influenced by environmental factors, while those of the constrained ordination are. Based on previous publications (Legendre, Legendre, Legendre, & Legendre, 2012; Lepš & Šmilauer, 2003), a summary of individual ordination approaches by Zelený (2018) is described in **Table 2.1**.

Table 2.1. Methods for unconstrained and constrained multivariate ordination.

Type	**Raw-data-based (Classical approach)**		**Transformation-based**	**Distance-based**
	Linear	**Unimodal**		
Unconstrained	Principal Component Analysis (PCA)	Correspondence Analysis & Detrended Correspondence Analysis (CA & DCA)	Transformed-based Principal Component Analysis (tb-PCA)	Principal Correspondence Analysis, Non-metric Multidimensional Scaling (PCoA, NMDS)
Constrained	Redundancy Analysis (RDA)	Canonical Correspondence Analysis (CCA)	Transformation-based Redundancy Analysis (tb-RDA)	Distance-based Redundancy Analysis (db-RDA)

Y. M. Zhang et al. (2005) argued that understanding environmental influences on a certain site can provide relevant information on adaptable species for that location and similar sites. As such, this study aims to 1) aggregate tree species data into different functional groups and 2) explore interactions between environmental variables, tree species composition and distributions of key functional groups. This study hypothesizes that environmental factors and species distributions of each tree species groups are significantly related.

MATERIALS AND METHODS

Data preparation

Data for the analyses were collected from the Forest Inventory and Planning Institution (FIPI) (hereafter DATA1). In 2005, 153 one-hectare permanent sample plots (PSPs) were established in 51 one-km^2 ecological permanent plots (EPPs) across the country (**Figure 2.1 and Figure 2.2**). The dbhs of approximately 100,000 trees and heights of approximately 50,000 trees were measured. All records with dbhs lower than 5.9 cm or those marked as “dead tree”, “standing death”, “hollow”, “liana”, “ tree top collapsed”, “tree top dead”, “tree top looped”, and “tree decayed” were excluded from this study. Scientific names, family names, and number of species and families occurring at each permanent sample plot were identified.

Environmental data were also collected for each site. Annual mean rainfall and temperature, and mean monthly solar radiation were taken from the WorldClim database (http://www.worldclim.org/) at a resolution of 30 seconds of latitude and logitude. Site characteristics (depth to bedrock and soil organic carbon stock), physical soil properties (bulk density, clay content, silt content and sand content) and chemical soil properties (cation exchange capacity of soil, soil organic carbon content and soil pH in KCl) were obtained from the International Soil Reference and Information Centre (ISRIC) (https://www.isric.org). These site characteristic and soil data were represented in raster layers with the resolution of 250 x 250 metres. General descriptions of each environmental variable are presented in **Table 2.2**.

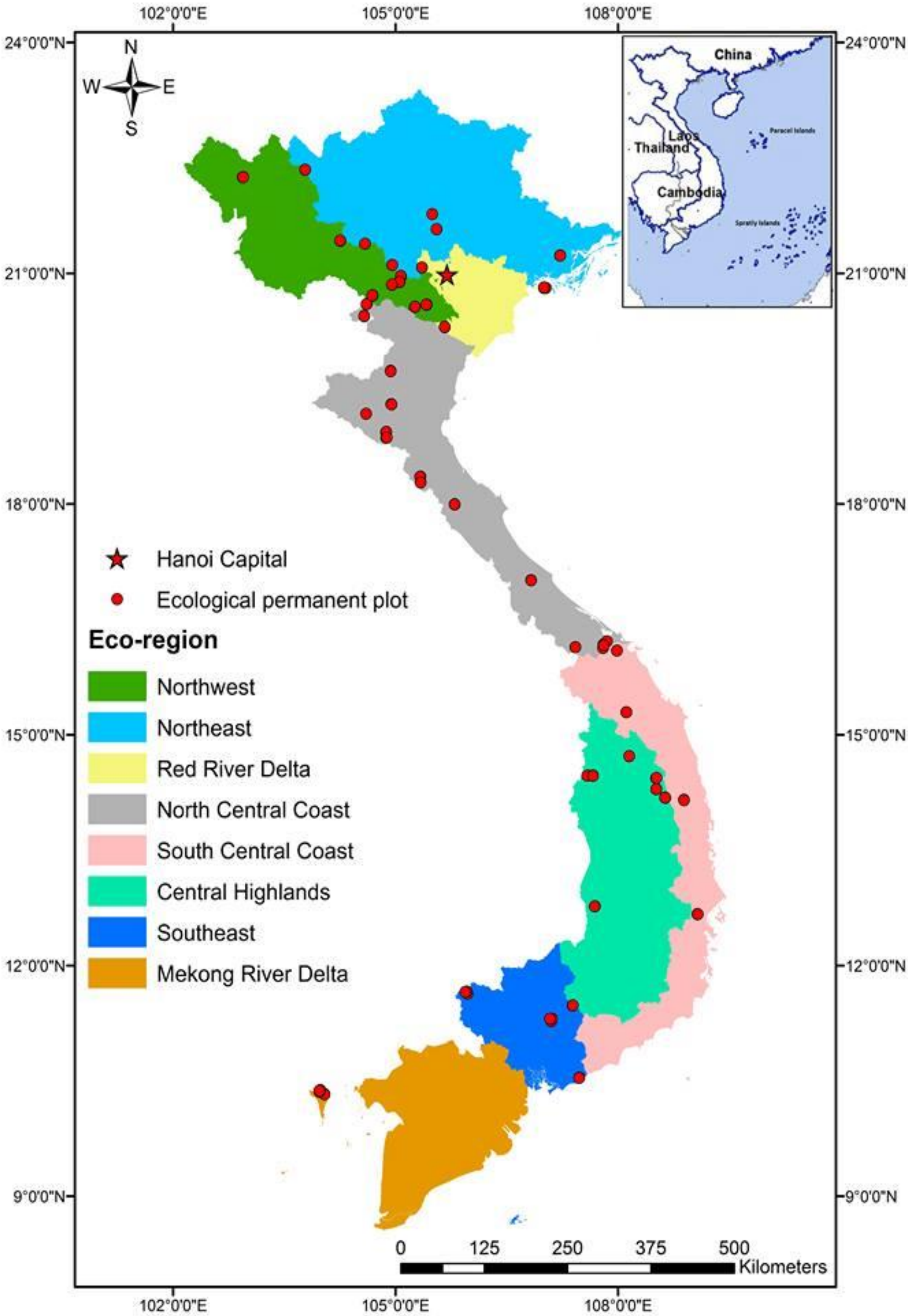

Figure 2.1. Location of the ecological permanent sample plots (1x1 km plots).

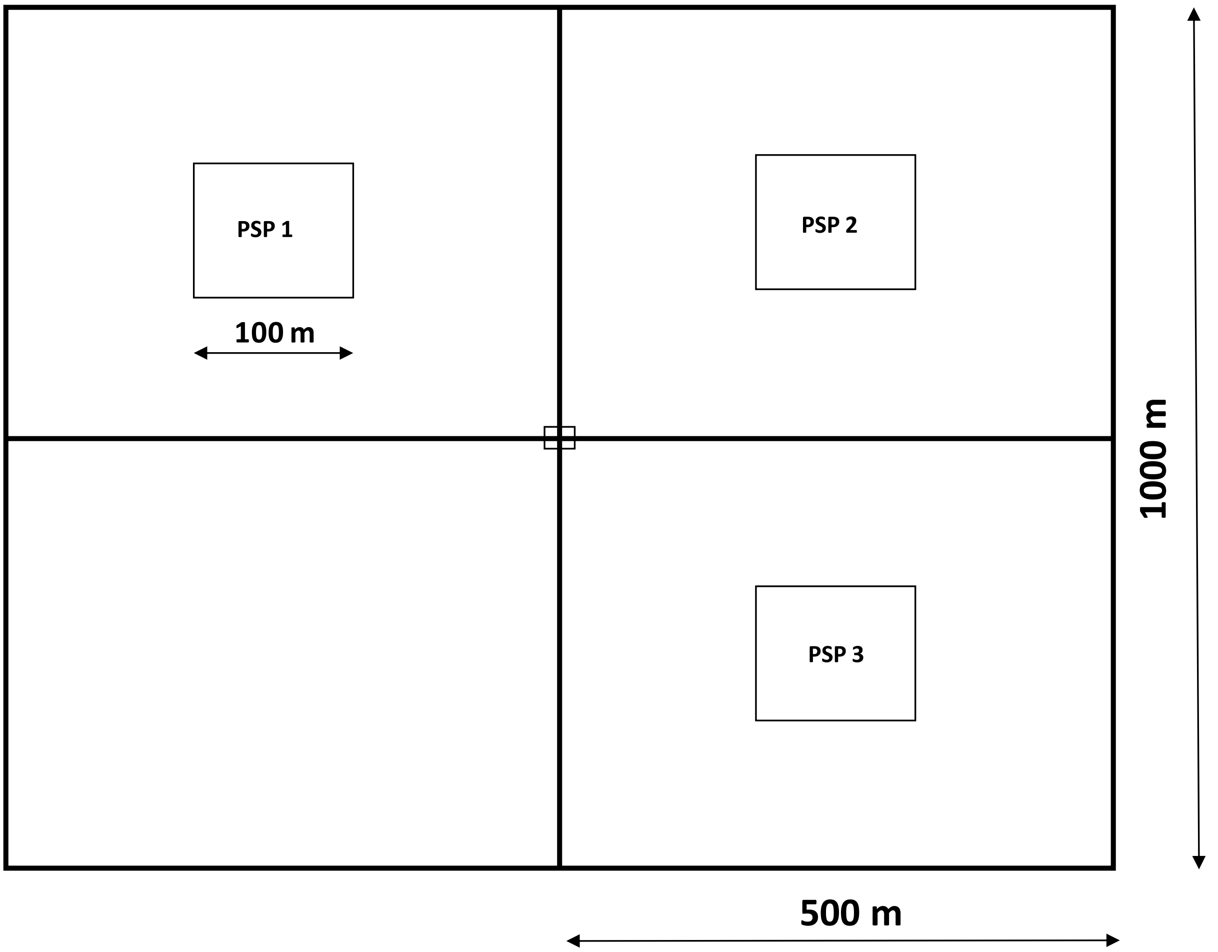

Figure 2.2. Design of PSPs and EPSs (1x1 km) developed by FIPI.

Worldclim data including monthly averages of climate as measured at weather stations from a large number of global, regional, national, and local sources, mostly for the 1950–2000 period. Climatic data for this current thesis were generated by using coordinates of each EPPs (site) to extract them from data layers of Worldclim. Soil data from the ISRIC were collected from a wide range of soil database organizations in the world. This database may come from previous studies and publications of various countries**.** A large number of other studies have used data issued by Worldclim and the ISRIC (Lim et al., 2018; Rong et al., 2019).

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Table 2.2. The environmental variables with their abbreviations and transformation type.

Variable	Abbreviation	Units	Transformation	λ
Elevation	Elev	m	Box - Cox	0.52
Mean rainfall	Rain	mm/year		-1.52
Mean temperature	Temp	^{0}C/year		2.25
Depth to bedrock	Brock	Cm		0.45
Soil organic carbon stock	CS	tones/ha		-1.44
Bulk density	Bulk	kg/m^3		1.88
Clay content	Clay	%		0.97
Silt content	Silt	%		2.28
Sand content	Sand	%		-1.28
Cation exchange capacity	Cex	cmolc/kg		-0.59
Soil organic carbon content	CC	g/kg		0.34
Solar radiation	Srad	kJ m^{-2} day^{-1}		
Soil pH in KCl	pH			0.17

λ (*lamda*): An exponent of the Box Cox transformation

Data analysis

Tree species grouping

Regeneration strategy and maximum attainable tree height of 401 tree species (see **APPENDIX I**) were collected from Vietnamese botanical books (Ho, 1999, 2001, 2003; Hop, 2002) and the internet source eFlora (eFlora, 2017). Regarding regeneration strategy, an ecological subjective approach was selected for the grouping purposes since it was easy to analyse over short periods of time and was applicable to tropical rain forests. Ecological data-driven methods require the measurement of trees with dbhs bigger than 10 cm, which is not applicable in DATA1. The dynamic process approach is based primarily on categories of dynamic characteristics only, which is not helpful when growth models are created with measurements of independent variables at only one point in time . Tree species were grouped as “shade intolerant”, “shade tolerant” and “moderately shade tolerant”, and a fourth group was created for species without regeneration strategy information. Several approaches were used to aggregate tree species into different groups such as agglomerative hierarchical clustering (Shryock, DeFalco, & Esque, 2014), optimal univariate clustering (Wang, 2011), and k-means clustering algorithm (Ethala, Seshadri, & Renganathan, 2013). The first and the second approaches showed a high number of unbalanced groups, and thus the third approach was used for aggregating species of each group by using the mean maximum attainable size (MMAS). Tree species groups were identified based on a combination of shade categories and attainable tree sizes for tree height modelling. The algorithms for k-means approaches (G. James, Witten, Hastie, & Tibshirani, 2014) are described as follows:

1. The number of clusters of the regeneration groups was selected if there is a sharp drop with respect to groups within the sum of squares in scree plots of the k-means clustering approach (**Figure 2.3**).

2. This is repeated until the cluster assignments stop changing:

- Assign each observation to one of the clusters
- Calculate the cluster means as the means of observation assigned to each cluster

- Assign each observation to the cluster whose centroid is closest (where closest is defined using Euclidean distance)

The algorithm is repeated multiple times using different random assigments in Step 1 and the best results will be chosen.

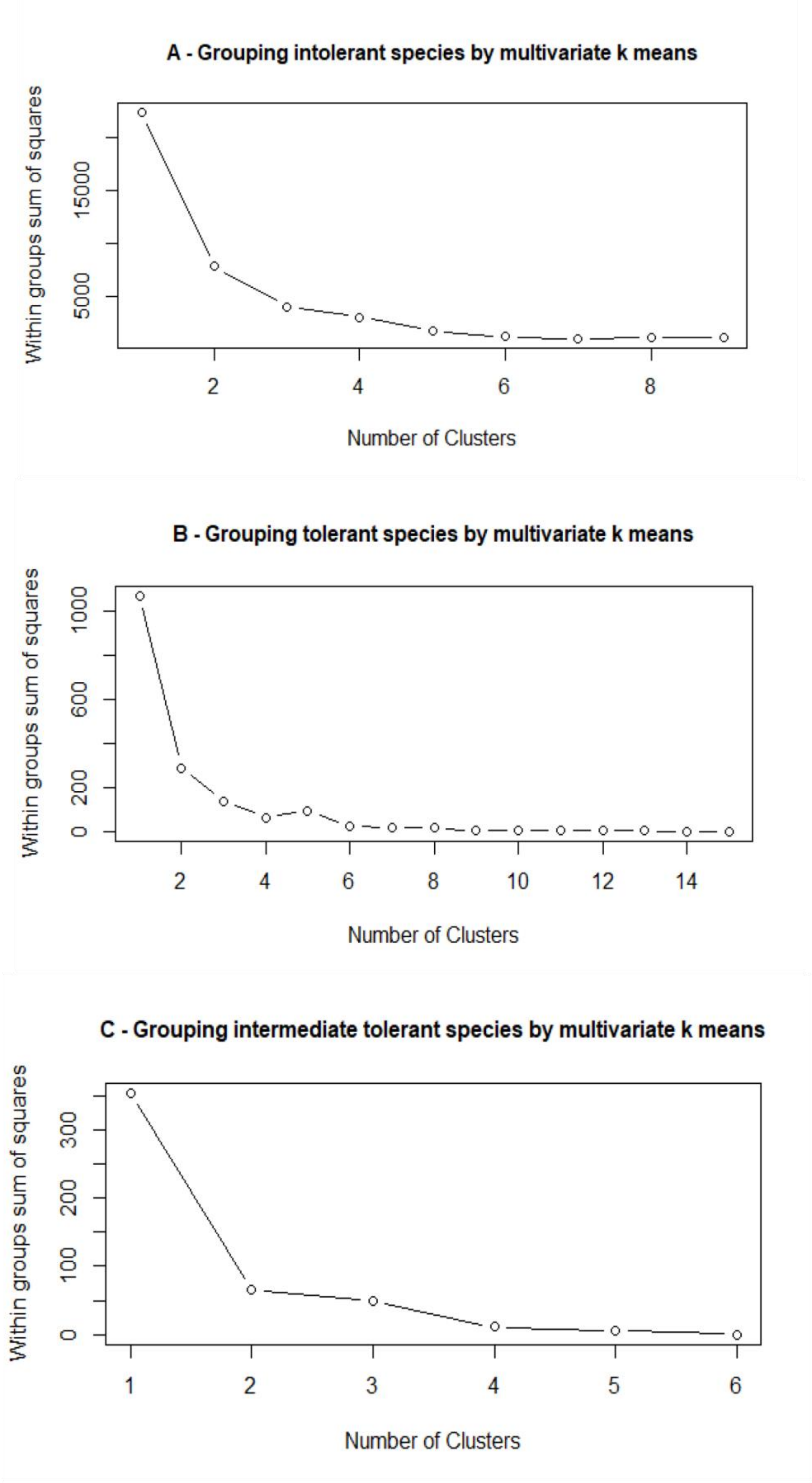

Figure 2.3. Scree plots of the k-means clustering analysis of regeneration groups.

Species-environment relationships

Three intolerant tree species groups were used to determine the relationships between species and environmental variables. This is because these groups comprised an estimated 72.31% of the total tree species, indicating wide distributions in the country. The initial ordination diagrams for PSPs and environmental factors were developed, which showed similar PSP patterns in the same EPPs with unclear distributions caused by a large number of PSPs. As such, the species-environment relationships were explored based on EPP units for better resolution of ordination diagrams.

Two different data matrices, comprising the species matrix and the matrix of environment variables, were created for ordination analyses of each tree species group (Svenning, Kinner, Stallard, Engelbrecht, & Wright, 2004; Van Nguyen et al., 2015). The species matrix included the number of stems per species/EPP. Any species absent in the sites were given a default value of '0'. The most common species with abbreviations of each tree species group are summarized in **Table 2.3**. The data matrix of the environmental variables was also constructed for 13 environmental factors from the same sites. Descriptive statistics of each environmental variables are described in **Table 2.4.**

Table 2.3. The most common tree species with abbreviations and number of sites in which these species existed.

Group	Species name	Abbreviations	Family	Number of sites
G1	*Diospyros sylvatica*	D.syl	Aceraceae	41
	Aglaia spectabilis	A.spe	Rubiaceae	39
	Litsea glutinosa	L.glu	Lauraceae	37
	Symplocos laurina var.acuminata	S.lau	Meliaceae	36
	Nephelium melliferum	N.mel	Euphorbiaceae	30
	Nephelium lappaceum	N.lap	Sapindaceae	17
	Lithocarpus proboscideus	L.pro	Phyllanthaceae	17
	Triadica cochinchinensis	T.coc	Euphorbiaceae	26
	Beilschmiedia percoriacea	B.per	Lauraceae	12
	Diospyros apiculata	D.api	Ebenaceae	28
	Elaeocarpus griffithii	E.gri	Elaeocarpaceae	34
G2	*Gironniera subaequalis*	G.sub	Ulmaceae	44
	Lithocarpus elegans	L.ele	Fagaceae	31
	Canarium tramdennum	C.tra	Burseraceae	37
	Polyalthia cerasoides	P.cer	Annonaceae	33
	Castanopsis chinensis	C.chi	Fagaceae	27
	Engelhardtia roxburghiana	E.rox	Combretaceae	38
	Acronychia pedunculata	A.ped	Lauraceae	31
	Cinnamomum ovatum	C.ova	Lauraceae	42
	Macaranga denticulata	M.den	Euphorbiaceae	33
	Ormosia pinnata	O.pin	Fabaceae	23
	Archidendron balansae	A.bal	Mimosaceae	29
	Cinnamomum parthenoxylon	C.par	Lauraceae	25
	Cratoxylum formosum	C.for	Hypericaceae	33
	Peltophorum pterocarpum	P.pte	Fabaceae	30
	Elaeocarpus petiolatus	E.pet	Elaeocarpaceae	19
G3	*Quercus platycalyx*	Q.pla	Fagaceae	25
	Lagerstroemia calyculata	L.cal	Lythraceae	8
	Parashorea chinensis	P.chi	Dipterocarpaceae	12
	Vatica tonkinensis	V.ton	Dipterocarpaceae	22
	Sassafras tzumu	S.tzu	Lauraceae	35
	Aphanamixis polystachya	A.pol	Meliaceae	38
	Machilus bonii	M.bon	Lauraceae	26
	Schima superba	S.sup	Theaceae	15
	Vatica diospyroides	V.dio	Dipterocarpaceae	11
	Artocarpus rigidus	A.rig	Moraceae	21

Table 2.4. Descriptive statistics of each environmental variables of the research sites.

Environmental Variable	Min	First quartile	Median	Mean	Third quartile	Max	Sd
Sil	22.00	28.50	31.00	30.69	33.00	37.00	3.44
Rain	1268	1578	1751	1895	2208	3527	465.88
CS	27.00	33.50	43.00	48.31	53.00	156.00	23.64
Elev	29.0	297.0	600	653.6	930	1981	448.57
Clay	24.0	28.0	30.0	30.1	32.0	37.0	3.09
Sand	31.00	37.00	39.00	39.69	41.00	55.00	4.6
Cex	14.00	21.00	23.00	23.57	25.00	41.00	4.7
Brock	0	1178	1679	2041	2212	7870	1496.98
CC	13.00	40.50	59.00	65.94	89.00	163.00	32.57
Temp	14.68	20.70	22.23	22.11	23.41	27.22	2.6
Srad	14323	14872	16237	16551	18151	19209	1676.27
pH	50.00	54.00	55.00	55.67	57.00	62.00	2.48
Bulk	1001	1120	1189	1180	1228	1343	77.32

Transformation-based Redundancy Analysis (tb-RDA) was employed to explore the relationship between tree species variation and environmental factors, using PC-ORD version 7 (Mc Cune, 2016). The Tb-RDA technique was applied since it comprises a combination of linear models and chi-squared distances, which was not included in the technique. These prevented biases that resulted from the use of other multivariate approaches of direct analysis of gradients, such as the canonical correspondence analysis (CCA) (de Maçaneiro, Oliveira, Seubert, Eisenlohr, & Schorn, 2016; Legendre & Gallagher, 2001; Legendre *et al*., 2012; Svenning *et al*., 2004). In tb-RDA, the number of explanatory variables determines the number of constrained axes. However, previous studies normally used the first three axes for ordination analysis (de Maçaneiro *et al*., 2016; Svenning *et al*., 2004), depending on the percentage of the variance. The ratio between the sum of the eigenvalues of constrained axes and the total inertia or the sum of eigenvalues of the constrained and the unconstrained axes can be utilized as a measure to evaluate how well species composition is explained by independent variables.

The Hellinger distance-transformed species data were employed to avoid biases caused by the Euclidean distances in RDA (Legendre & Gallagher, 2001). A Box-Cox transformation (Box & Cox, 1964) approach was used on environmental variables to correct differences in scale (de Maçaneiro *et al.*, 2016; Zar, 2010). Since there was a large number of tree species in each group, the preliminary tb-RDA ordination was implemented to explore any species that showed a weak correlation with selected environmental variables. These species were excluded from the species matrix for official tb-RDA analysis in PCORD.

Preliminary tb-RDA analyses included the following steps (Zelený, 2018). First, a global model including all environmental variables is tested to determine whether the overall model was significant. If the global model was statistically significant, then forward selection was applied to determine a subset of environmental variables. Function ordistep (Jari Oksanen, McGlinn, & Wagne, 2018) was used to perform step-wise selection of environmental variables based on their p-value and values of the AIC criterion (see **Table 2.5**). The purpose was to ensure dual benefits, which included 1) reducing the number of environmental variables involving tb-RDA and 2) keeping the adjustment explained by the variables to maximum (Zelený, 2018). These steps were completed in the computer program R for Windows version 3.4.1. Finally, the species matrix was transformed into the whole tree species of each group, while the selected environmental variables were used as inputs for PCORD in the initial tb-RDA.

Spearman's correlation coefficients were applied to determine correlations between environmental factors, tree species, and the first two tb-RDA axes. In addition, Monte Carlo permutation tests were used to evaluate the variation explained by environmental variables (Hejcmanovā-Nežerková & Hejcman, 2006; Zelený, 2018). If p values generated from the permutation tested lower than 0.05, then the variance was concluded to be higher than the variance explained through random environmental variables.

Table 2.5. A forward selection of explanatory environmental variables available for constrained ordination.

Group	Sil	Rain	CS	Elev	Clay	Sand	Cex	Brock	CC	Temp	Srad	pH	Bulk
Group 1 (p-value)	0.25	0.015 *	0.61	0.295	0.005 **	0.13	0.015 *	0.005 **	0.585	0.29	0.005 **	0.13	0.245
Group 1 (AIC)	-19.584	-20.259	-19.285	-19.563	-20.418	-19.773	-20.497	-20.603	-19.316	-19.577	-19.506	-19.792	-19.545
Group 2 (p-	0.200	0.140	0.240	0.220	0.005 **	0.385	0.070	0.005 **	0.010 **	0.005 **	0.005 **	0.125	0.270
Group 2 (AIC)	-17.721	-17.799	-17.697	-17.759	-19.028	-17.610	-18.384	-17.882	-18.813	-18.414	-19.001	-17.840	-17.704
Group 3 (p-value)	0.500	0.005 **	0.305	0.115	0.005 **	0.665	0.505	0.005 **	0.175	0.090	0.005 **	0.375	0.175
Group 3 (AIC)	-15.368	-16.396	-15.486	-15.821	-16.256	-15.296	-15.383	-16.314	-15.672	-15.817	-16.290	-15.427	-15.671

RESULTS

Species aggregation

Scree plots of the k-means clustering analysis showed that the most appropriate clusters for shade intolerance, shade tolerance and moderate shade tolerance groups were 3, 2 and 3, respectively (**Figure 2.3**). Thus, eight main functional groups were established by using the regeneration strategy and maximum attainable tree height, while the ninth group was created for species with missing information on the attainable size and scientific name. Details of each group were as follows:

- Group 1 (G1): Intolerant species and mean MMAS of 33.53 m,
- Group 2 (G2): Intolerant species and MMAS of 21.94 m,
- Group 3 (G3): Intolerant species and MMAS of 12.88 m,
- Group 4 (G4): Tolerant species and MMAS of 27.20 m,
- Group 5 (G5): Tolerant species and MMAS of 20.86 m,
- Group 6 (G6): Tolerant species and MMAS of 13.38 m,
- Group 7 (G7): Intermediate shade species and MMAS of 18.87 m,
- Group 8 (G8): Intermediate shade species and MMAS of 27.11 m.

The numbers of tree species in shade tolerant, intermediate tolerant and missing shade tolerance groups were only 36, 17, and 47, respectively. There were 290 species in shade intolerant classes recorded, which was approximately equivalent to 72.5% of the total number of species. The dbh and tree height mean of the intolerant groups including G1 (11.43 m), G2 (11.88 m) and G3 (14.13 m) was higher than that of the intermediate shade groups (G7 and G8) and the shade tolerant ones (G4, G5 and G6), respectively (**Table 2.6**).

Table 2.6. Description of functional groups aggregated by regeneration strategy and attainable tree height of tree species.

Group	Main species			Number of species/Family	Number of observations (tree)	$\overline{dbh}$ (cm; ±SD)	$\overline{H}$ (m; ±SD)
G1	*Diospyros sylvatica* *Nephelium lappaceum* *Aglaia spectabilis* *Litsea glutinosa* *Symplocos laurina*	*Diospyros apiculate* *Lithocarpus proboscideus* *Triadica cochinchinensis* *Memecylon edule* *Beilschmiedia percoriacea*	*Mallotus paniculatus* *Trema orientalis* *Colona auriculate* *Zanthoxylum avicennae* *Artocarpus lakoocha*	74/34	10039	*15.51* *(±10.40)*	*11.43* *(±4.23)*
G2	*Gironniera subaequalis* *Canarium tramdennum* *Lithocarpus elegans* *Canarium album* *Polyalthia cerasoides*	*Polyalthia thorelii* *Castanopsis chinensis* *Cinnamomum ovatum* *Engelhardtia roxburghiana* *Ormosia pinnata*	*Archidendron balansae* *Macaranga denticulate* *Cratoxylum formosum* *Cinnamomum parthenoxylon* *Peltophorum pterocarpum*	179/55	25374	17.03 *(±12.07)*	11.88 *(±4.49)*
G 3	*Lagerstroemia calyculata* *Quercus platycalyx* *Parashorea chinensis* *Vatica tonkinensis*	*Sassafras tzumu* *Aphanamixis polystachya* *Schima superba* *Wrightia annamensis*	*Machilus bonii* *Endospermum chinense* *Machilus odoratissimus* *Vatica diospyroides*	46/24	*6910*	*22.71* *(±19.37)*	*14.13* *(± 5.92)*
G4	*Knema pierrei* *Hydnocarpus kurzii* *Ixonanthes chinensis*	*Garcinia oblongifolia* *Streblus macrophyllus* *Diospyros nitida*	*Syzygium cumini* *Symplocos dolichotricha* *Symplocos macrophylla*	15/11	*2575*	14.89 (±9.00)	*11.52* *(±4.04)*
G5	*Knema globularia* *Symingtonia populnea*	*Aidia oxyodonta* *Podocarpus neriifolius*	*Calophyllum membranaceum*	5/5	*722*	14.34 (±10.03)	10.41 *(±4.23)*
G6	*Schefflera heptaphylla* *Syzygium jambos* *Streblus indicus*	*Pometia pinnata* *Gordonia tonkinensis* *Ficus septica*	*Microdesmis caseariifolia* *Canthium dicoccum* *Michelia balansae*	18/13	*1570*	15.86 (±*11.26)*	*10.63* *(±4.08)*
G7	*Syzygium zeylanicum* *Cleistanthus sumatranus*	*Vernonia arborea* *Lithocarpus balansae*	*Bursera tonkinensis* *Acer flabellatum*	8/8	*1355*	16.95 (±11.75)	12.03 *(±4.41)*
G8	*Dimocarpus fumatus* *Buchanania arborescens*	*Manglietia fordiana* *Lithocarpus harmandii*	*Litsea verticillate* *Cinnadenia paniculate*	*9/8*	*504*	16.78 (±13.23)	11.54 (±4.39)
G9	*Phoebe kunstleri* *Gonocaryum lobbianum* *Taxatrophis ilicifolia*	*Saurauia napaulensis* *Sterculia lanceolate* *Jatropha multijida*	*Syzygium chanlos* *Glenniea philippinensis* *Camellia chrysantha*	*48/28*	*2288*	18.45 (±13.16*)*	11.74 (±4.34)

Ordination analysis (tb-RDA)

The Eigenvalues show the amount of variation in the total sample accounted for by each factor. The Eigenvalues of the first two tb-RDA axes of different tree species groups is presented in **Table 2.7**. The sums of the eigenvalues of the constrained axes of three species groups were 19.71% to 24.43% of the variance. Eigenvalues of the first tb-RDA axes were from 8.78% to 9.3% of the variance. Meanwhile the values of the second tb-RDA axes identified lower percentages of variance that ranged from 6.0% to 7.5%. Lastly, the eigenvalues of the tb-RDA axes of different groups appeared highly significant ($p < 0.001$).

Table 2.7. Results of the RDA and Monte Carlo permutations for testing the significance of environmental variables with regards to tree species distribution patterns of groups.

Tree species group	**Engenvalue**		**Sum of all canonical axes**	
	tb-RDA 1	**tb-RDA 2**	**Eigenvalue**	**P value in F test**
G1	0.058	0.047	0.1528	***
Percentage explained	9.3	7.5	24.43	
G2	0.038	0.033	0.1044	***
Percentage explained	8.9	7.6	24.19	
G3	0.049	0.031	0.1013	***
Percentage explained	9.5	6.0	19.71	

Note: Statistical analyses are significant at 95% confidence interval. *** $p < .0001$.

<u>Group 1:</u>

Group 1 included 32 tree species, which showed significant correlations with the first two tb-RDA axes in the Spearman's correlation test. Tb-RDA indicated 24.3% of the total variance of the G1 dataset ($P < 0.001$). Tb-RDA 1 explained 9.3% of the total variance or 30.7% of the constrained variability; while Tb-RDA 2 explained 7.6% of the total variance or 31.41% of the constrained variability. The first axis correlated positively with solar radiation, rainfall and depth to bedrock, but correlated negatively with clay content at $p < 0.001$ (see **Figure 2.4A** and **Figure 2.4B**). In regards to species, the first tb-RDA 1 was mainly correlated with *G. eriocarpum*, *O. semicastrata*, *D. hookeri*, *T. orientalis* and *C. petelotii*. The second tb-RDA axis correlated negatively with both solar radiation and clay content at $p < 0.001$. The axis was mainly correlated with *L. cubeba*, *D. maritima*, *D. apiculata*, *R. verticillata* and *S. siamea*.

Correlations between tb-RDA axes and selected environmental factors are presented in **Table 2.8**. Solar radiation showed the strongest correlation with the first axis ($R = 0.87$), while clay content represented the highest value of R in the second axis. Solar radiation was positively correlated to *O. cambodiana* and *D. sylvatica,* which are widely distributed in different regions including North Central Coast, Central Highlands and South Central Coast. Clay content is closely correlated with *A. lakoocha*, *S. laurina var.acuminata* and *T. cochinchinensis,* which are found in North Central Coast region.

Table 2.8. Summary of correlations between environmental variables and tb-RDA axes, using Spearman's correlation ranks.

Group	Environmental factor	R	
		tb-RDA 1	tb-RDA 2
G1	Srad	0.87***	-0.58***
	Clay	-0.08	-0.70***
	Brock	0.58***	0.13
	Rain	0.46***	0.10
	Cex	-0.05	0.11
G2	Brock	-0.34*	0.69***
	Temp	0.15	-0.61***
	Clay	0.84***	0.21
	Srad	0.22	-0.9***
	CC	0.12	0.23
G3	Brock	0.9***	-0.18
	Srad	0.65***	0.28*
	Rain	0.21	-0.8***
	Clay	0.07	0.39**

Note: Statistical analyses are significant at 95% confidence interval. $^{***}p < .001$; $^{**}p < 0.01$; and $^{*}p < 0.05$.

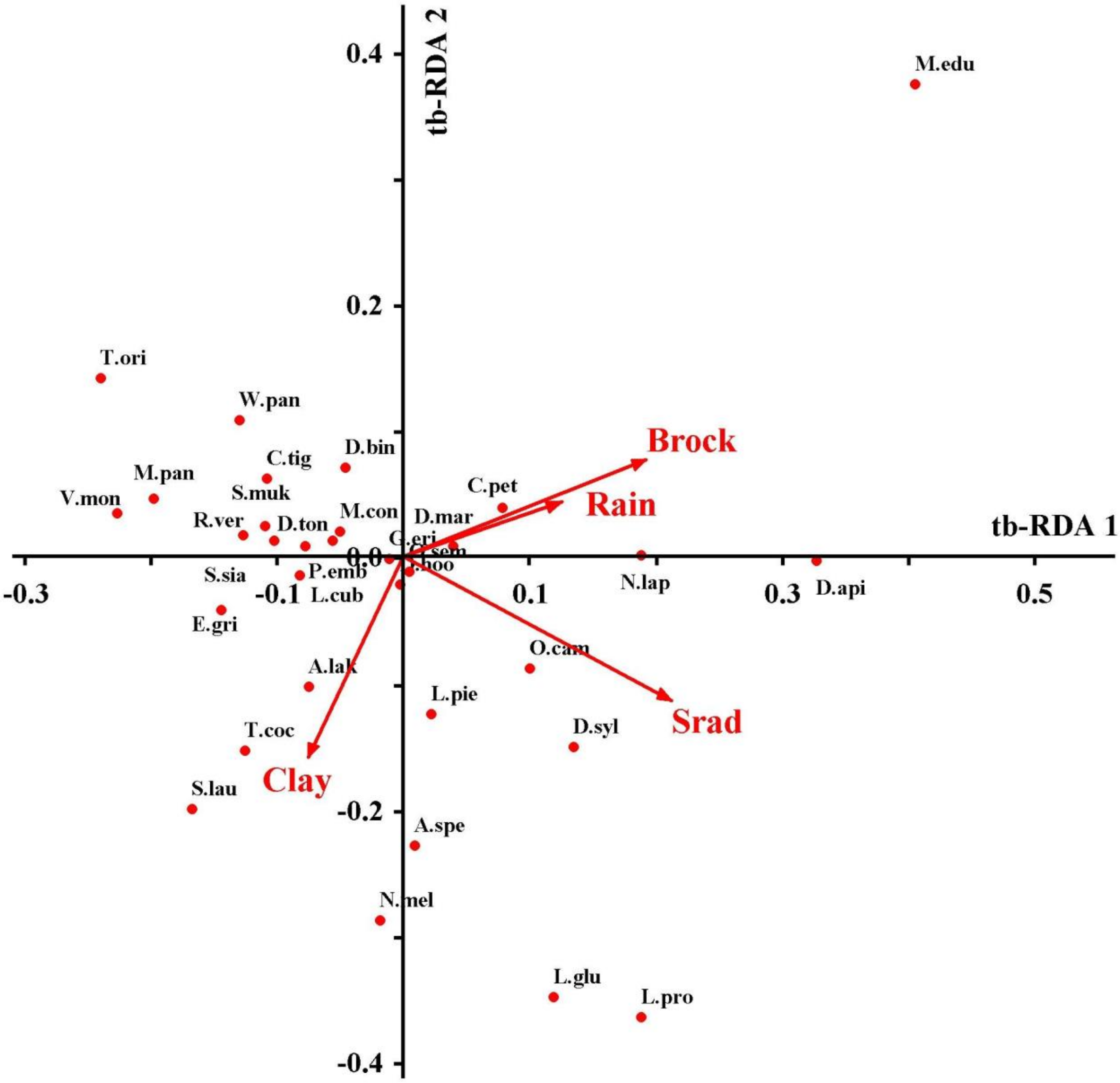

Figure 2.4A. Diagram produced by tb-RDA to species, with arrows representing the environmental factors and symbols describing 32 species of G1. For species abbreviations see **Appendix I**. For the abbreviations of environmental factors see **Table 2.2.**

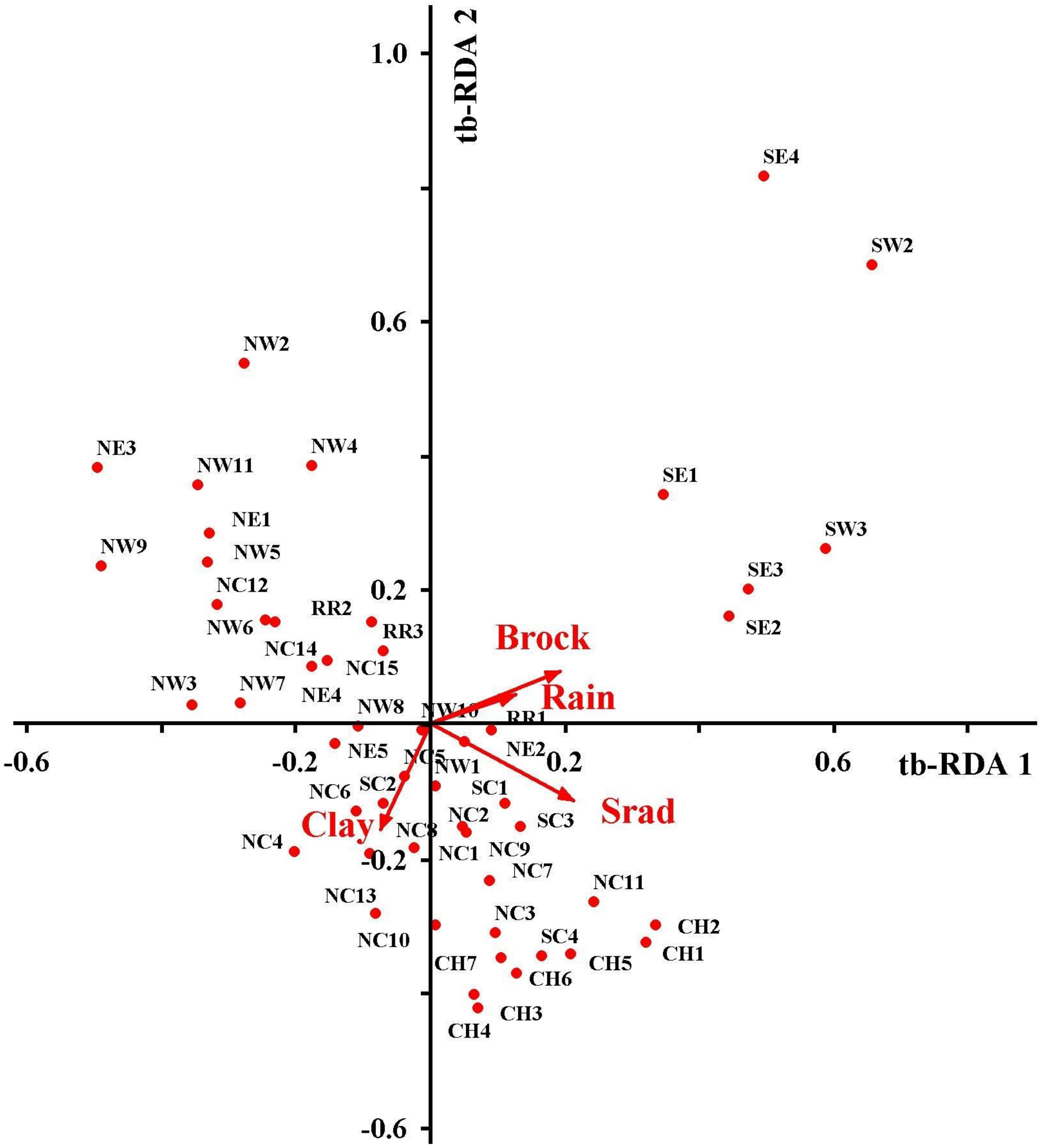

Figure 2.4B. Diagram produced by tb-RDA to EPPs, with arrows representing the environmental factors and symbols describing 51 EPPs where species of G1 locate. Key to abbreviations of EPPS: NW: Northwest; NC: North Central Coast; NE: Northeast; CH: Central Highlands; SE: Southeast: SW: Southwest; RR: Red River Delta; SC: South Central Coast. For the abbreviations of environmental factors see **Table 2.2.**

The gradients of environmental variables and the distribution patterns of tree species presented some groups of species. The first group of species was associated with EPPs, which are mainly located in Northwest and Northeast region, characterised by low depth to bedrock and low solar radiation with high clay content (e.g. *T. orientalis, W. paniculata, V. montana, M. paniculata, S. mukorossi, C. tiglium)*. Another group of species was found to be strongly associated with EPPs with low clay content, which are mainly located in North and South Central Coast, and Central Highlands (e.g. *L. proboscideus, L. glutinosa, N. melliferum, A. spectabilis).* Finally, *M. edule* was also found to be highly associated with clay content, and was mainly distributed in Southeast and Southwest Vietnam.

Group 2:

Group 2 included 74 tree species that showed significant correlations with two tb-RDA axes ($p < 0.05$). Tb-RDA revealed that 24.19% of the tree data was influenced by the selected environmental variables, of which tb-RDA 1 had 8.9% of the total variance or 36.79% of the constrained variability. Meanwhile, the second axis explained 7.6% of the total variance or 31.41% of the constrained variability. The first tb-RDA axis correlated positively with solar radiation, depth to bedrock and temperature ($p < 0.001$). The axis is chiefly correlated with *A. ridleyi, G. subaequalis, O. pinnata, G. xanthochymus, C. parthenoxylon, E. petiolatus, C. chinensis* and *A. pilosa*. The second axis was negatively correlated with all environmental variables, of which solar radiation showed the highest correlation with tb-RDA 2 ($p < 0.001$) (see **Table 2.7** and **Figure 2.5A**). This axis was strongly correlated with *P. cerasoides, P. annamensis, E. roxburghiana, A. clypearia, P. thorelii, D. turbinate, G. oliveri* and *V. sumatrana.*

Clay content was closely related to the dominance of species mainly distributed in the North Central Coast of Vietnam, including *A. ridleyi, A. indicus, A. balansae* and *G. xanthochymus.* Mean annual temperature and solar radiation were closely linked to the communities of *B. sapida and S. macropodum,* which is chiefly found in the Central Highlands region. Finally, species such as *H. hainanensis, V. sumatrana var.urceolata, P. annamensis* and *S. saman* were positively correlated with depth to bedrock, and are largely distributed in Southeast Vietnam.

Figure 2.5A. Diagram produced by tb-RDA to species, with arrows representing the environmental factors and symbols describing 74 species of G2. For species abbreviations see **Appendix I**. For the abbreviations of environmental factors see **Table 2.2.**

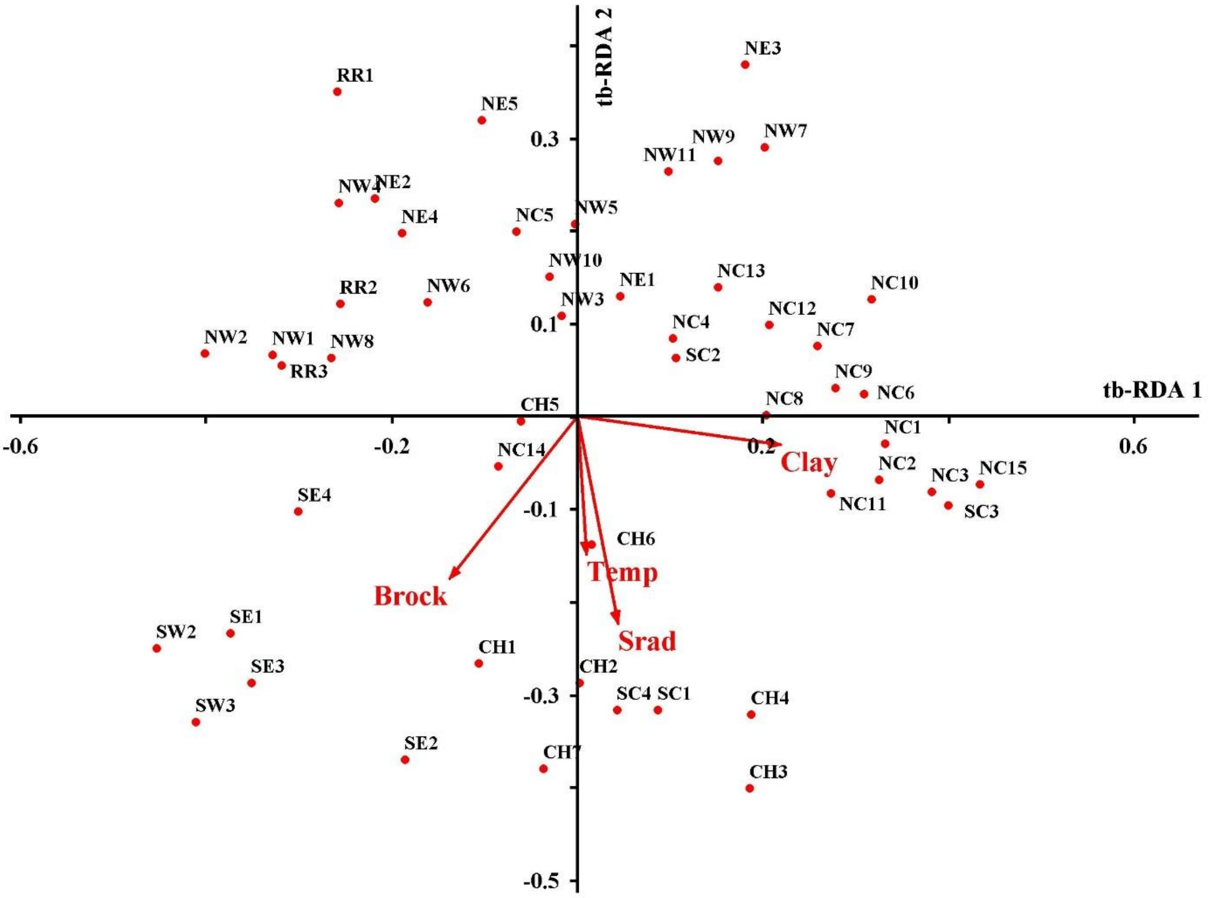

Figure 2.5B. Diagram produced by tb-RDA to EPPs, with arrows representing the environmental factors and symbols describing 51 EPPs where species of G2 locate. Key to abbreviations of EPPS: NW: Northwest; NC: North Central Coast; NE: Northeast; CH: Central Highlands; SE: Southeast: SW: Southwest; RR: Red River Delta; SC: South Central Coast. For the abbreviations of environmental factors see **Table 2.2.**

Similar to Group 1, some species groups sharing the same characteristics were also defined. The first group included tree species distributed in EPPs with high solar radiation and high depth to bedrock (e.g. *E. roxburghiana, C. chinensis, A. clypearia. Tonkinensis, C. parthenoxylon)*. These species were mainly found in the Northeast and Northwest of Vietnam (see **Figure 2.5B**). Additionally, another group of species apparently required high solar radiation and low clay content, and was mostly scattered in the Red River Delta and Northwest Vietnam (e.g. *E. petiolatus, C. tonkinensis, C. javanica subsp. nodosa, A. villosa, L. rhodostegia, C. axillaris, F. racemose, D. turbinate*). The main distributed areas of these tree species were in Red

River Delta and Northwest of the country. Finally, a group of species including *X. noronhiana, V. cinerea, G. hanburyi* and *S. saman*, was mainly scattered in Southeast and Southwest Vietnam, and was found to be strongly associated with low clay content.

Group 3:

The last group included 26 tree species, which showed significant correlations with two tb-RDA axes in the Spearman test ($p < 0.05$). The Eigenvalues of the first two tb-RDA axes explained 15.5% of the variance (tb-RDA 1 = 9.5%, tb-RDA 2 = 6%). The first tb-RDA axis correlated positively with clay content and solar radiation ($p < 0.001$). Species were found to be strongly correlated with the first axis including *Q. platycalyx, P. chinensis and E. chinense.* The second axis was negatively correlated with rainfall ($p < 0.001$) and positively with clay content ($p < 0.01$) (see **Table 2.7** and **Figure 2.6A**). This axis was mainly correlated with *M. bonii, A. polystachya* and *V.canescens.*

Rainfall was found to be linked mainly to the dominance of *V. canescens* which is primarily distributed in the North Central Coast, Northeast, Northwest and South Central Coast of Vietnam. Depth to bedrock was strongly correlated with *L. calyculata and A. costata*, which is largely distributed in the Central Highlands and Northeast Vietnam. Finally, solar radiation was found to be strongly linked to the canopy of *D. loureiri and P. chinensis*, mainly distributed in the Central Highlands and North Central Coast regions.

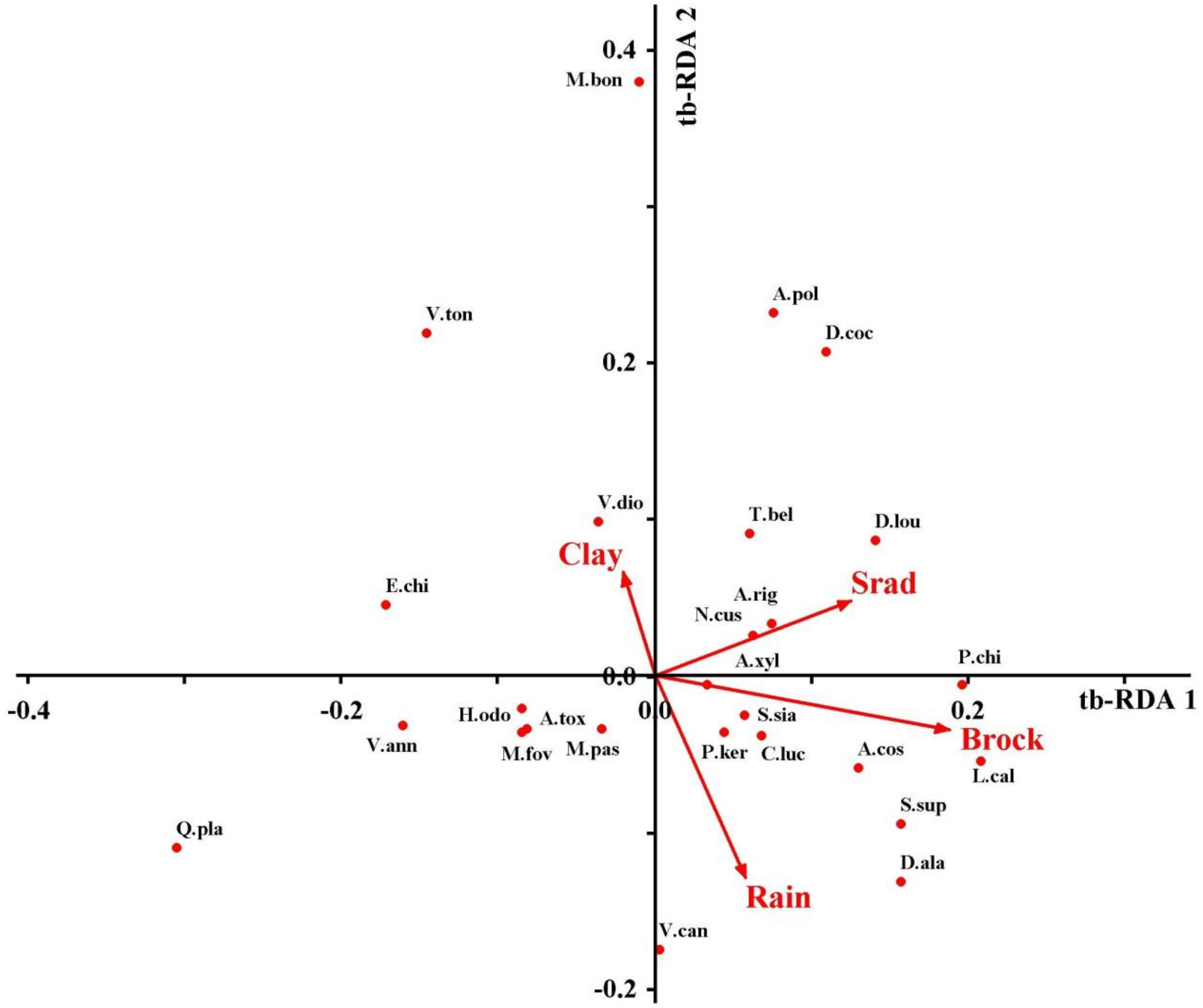

Figure 2.6A. Diagram produced by tb-RDA to species, with arrows representing the environmental factors and symbols describing 26 species of G3. For species abbreviations see **Appendix I**. For the abbreviations of environmental factors see **Table 2.2.**

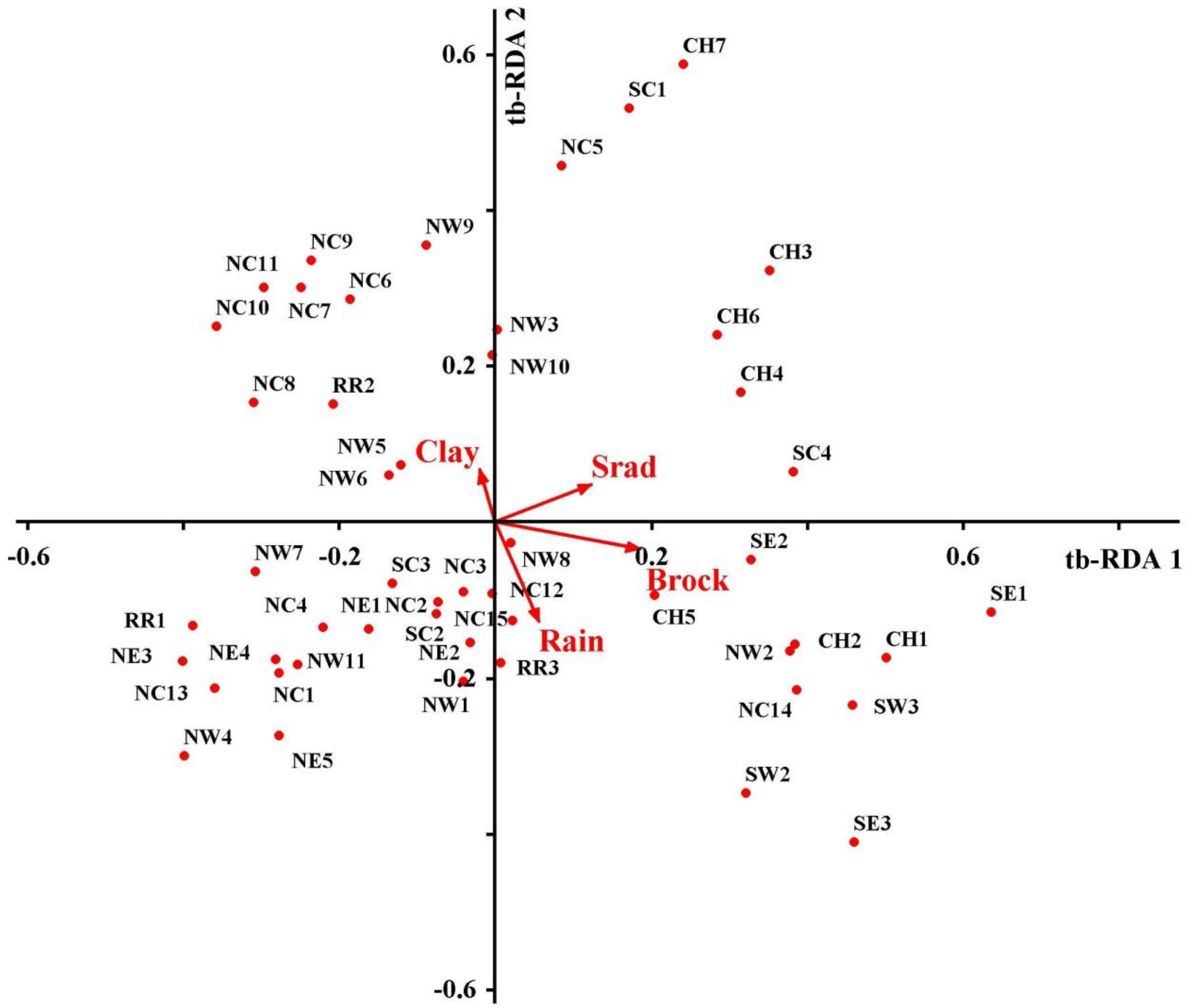

Figure 2.6B. Diagram produced by tb-RDA to EPPs, with arrows representing the environmental factors and symbols describing 50 EPPs where species of G3 locate. Key to abbreviations of EPPS: NW: Northwest; NC: North Central Coast; NE: Northeast; CH: Central Highlands; SE: Southeast: SW: Southwest; RR: Red River Delta; SC: South Central Coast. For the abbreviations of environmental factors see **Table 2.2.**

Figure 2.6A and **figure 2.6B** shows groups sharing similar patterns of species and local patterns. The first group was significantly influenced by a high level of rainfall, which includes species such as *M. bonii, V. tonkinensis, A. polystachya and D. cochinchinense.* These species are widely distributed in North Central Coast and South Central Coast of Vietnam. The second group of species, which is mainly found in the Northeast and Northwest Vietnam, was under the effect of low depth to bedrock, including *Q. platycalyx, E. chinense, W. annamensis* and *M. foveolata.* The last group of tree species included species such as *D. alatus, S. superb* and *A. costata,* is found in Southwest and Southeast regions of the country and was under the effect of both rainfall and depth to bedrock.

DISCUSSION

In this chapter, more than 400 tree species from over 50,000 individual trees distributed in 153 PSPs belonging to 51 EPPs were aggregated into nine functional groups based on regeneration strategy and MMAS. Studies on tree species aggregation, forest growth and forest modelling using species grouping approaches have been implemented for years (Adame et al., 2014; Masripatin, 1998; Vanclay, 1991). As stated by Masripatin (1998), the role of tree species grouping in reducing variation in modelling and in improving the efficiency of models is important.

The ordination technique has a few weaknesses in showing direct correlations among environmental variables and the distributions of tree species; however, it has been widely used in forest ecology as the most effective approach for showing the direction of environmental influences. The results of the recent study showed that there was five environmental variables showing an influence on the distribution patterns of shade-intolerant tree species in evergreen broadleaf forests in Vietnam. There were three tree species groups that shared the same influential environmental factors in their species distribution patterns, including clay content, solar radiation and depth to bedrock. These characteristics could be explained by the fact that all three groups were originally intolerant tree species, thus they may have the same influential environmental factors. Previous studies showed that topographic characteristics play a key role in driving the distribution of tree species (Arévalo, Cortés-Selva, & Chiarucci, 2012; Tardella *et al.*, 2017). However, due to the lack of information describing slope and aspect, only altitude was used for tb-RDA and found no effects of this environmental variable on tree species communities of DATA1. Thus, the lack of information on slope and aspect could be considered as a major challenge in recent studies.

For decades, the importance of solar radiation in plant ecology has been recognized (Piedallu & Gégout, 2008). In this study, ordination analyses of three tree groups showed that solar radiation was significantly correlated with all tb-RAD axes (see **Table 2.7**). But there was an inconsistency between this study and the previous study (Dorji, Moe, Klein, & Totland, 2014) on species composition and distributions that were significantly associated with solar radiation. In the study made by Dorji *et al*. (2014) exploring how plant community properties interacted along gradients of different environmental factors in China's Central Tibet, they concluded that species composition was significantly linked with a large number of environmental variables but not solar radiation. Thus, the findings in this study were consistent with the conclusions on the distribution and composition of ecosystems based on leaf photosynthesis, which are strongly influenced by solar radiation (Gates, 1980; Satterlund & Means, 1978).

Soil depth to bedrock is also an important environmental indicator contributing to plant growth (Abd-Elmabod *et al*., 2017). However, studies on this topic were quite limited. Only a few publications were found to be related to the influence of soil depth to plant species, and limited to non-forest tree species. All conclusions from these previous publications supported the assumption that the distribution and composition of plant communities were significantly affected by soil depth. Soil depth was considered one of the most important environmental factors influencing the distribution of 18 herbaceous species in Goose Lake Prairie, USA (Nelson & Anderson, 1983). Another study pointed out that the patterns in species composition within the Edwards Plateau Land Resource Area, USA were dependent on soil depth (Fuhlendorf & Smeins, 1998). Consistent with these previous studies, soil depth to bedrock was found to have played an important role in species composition and distribution of the whole tree species groups.

Moreover, soil was considered as one of the most influential factors affecting plant communities (Zare Chahouki, Khojasteh, & Tavili, 2012), which leads to changes in species composition among forests (Swamy, Sundarapandian, Chandrasekar, & Chandrasekaran, 2000). A large number of soil properties was used to explore the relationship between environmental factors and tree species composition and distribution of the evergreen broadleaf forests. However, only the influence of clay content on the species patterns was recognized as significant. This finding was supported by a study conducted by (Van Nguyen et al., 2015) that explored the effects of environmental factors on the abundance and presence of tree species in tropical limestone forests in Ben En National Park, Vietnam. Clay content was also considered to be a driving force that significantly affected tree species in tropical forests (Sarvade, Gupta, & Singh, 2016). The tb-RDA results of the present study indicated that soil content represented an important influence to species such as *A. lakoocha*, *S. laurina var.acuminata* and *T. cochinchinensis* (**Figure 2.4A**), *A. ridleyi, A. indicus, A. balansae* and *G. xanthochymus* (**Figure 2.5A**).

Mean annual temperature and rainfall were two climatic factors which showed significant correlations with one of two tb-RDA axes (**Table 2.7**). The influence of rainfall on species richness, composition and distribution at a large scale has been recorded in a number of previous studies (Amissah, Mohren, Bongers, Hawthorne, & Poorter, 2014; Hall & Swaine, 1976; Toledo *et al.*, 2012; von Hildebrand *et al.*, 2006).

Studies are still limited regarding the response of tropical forests on temperature (Amissah *et al.*, 2014). However, recent studies indicated that species distribution is likely to be affected by minor changes in temperature (Wright, 2010). In a related study in Ghana, rainfall was found to be the main factor shaping tree species distribution, but there was much less variation (Amissah *et al.*, 2014). Another study on species diversity, stand structure, and species distribution of tropical forests in Myanmar showed that species diversity and richness were significantly linked with rain fall and average temperature (Khaine *et al.*, 2017). The findings of the recent study were consistent with the aforementioned discussion linked to previous studies, which may provide invaluable information for forest managers and ecological phyto-geographers (Khaine *et al.*, 2017).

CONCLUSION

Nine tree species groups were successfully aggregated, based on tolerant characteristics and mean maximum attainable size of each tree species. There were three intolerant groups (G1, G2 and G3) including more than 72.30 % of tree species that were used to explore the relationship of environmental variables and species distribution. This study found that species distributions were significantly correlated with solar radiation, soil depth to bedrock, and clay content in all three species groups. While annual rainfall was significantly associated with species distribution G1 and G3; annual temperature was significantly linked with species distribution in G2. The significant correlations between the aforementioned environmental factors and species distribution in three groups are consistent with findings from previous studies, but not in the case of solar radiation. The findings of the recent study have attempted to approximate the distribution of tree species that significantly correlated with environmental factors by EPPS in each ecoregions. For example species such as *O. cambodiana* and *D. sylvatica* (G1), *B. sapida* and *S. macropodum* (G2), and *D. loureiri* and *P. chinensis* (G3) of related regions strongly associated with solar radiation. The results from this study might be good information for forest managers in terms of making appropriate species choices for forest rehabilitation and reforestation programs in Vietnam.

One of the many drawbacks of this study was that the influences of topographic patterns on tree species distribution were not completely examined due to the limited information about slope and aspect. Therefore, further studies are encouraged on species distribution on tropical forest in general, and on the enrivonmental factors that affect evergreen broadleaf forests in Vietnam.

CHAPTER 3

TREE HEIGHT AND DIAMETER AT BREAST HEIGHT MODELS USING SPECIES AGGREGATION APPROACH

INTRODUCTION

In forest inventories, individual tree height is one of the most important variables that needs to be measured. It is used for estimation of tree biomass, timber volume, site index, carbon stock, and growth and yield models (J. Chave et al., 2005; Kearsley et al., 2017; C. Peng, Zhang, & Liu, 2001). But generally, tree height measurement is time-consuming and costly (Wagle & Sharma, 2012), which is especially true in tropical forests (da Silva Scaranello *et al.*, 2012). The most difficult challenge in developing H-D models in tropical forests is having a large number of tree species with very limited records (Lam *et al.*, 2017).

Tree height plays a vital role in estimating forest biomass accurately (J. Chave et al., 2005; Feldpausch et al., 2012; Hunter, Keller, Victoria, & Morton, 2013; Kearsley et al., 2017; Ledo et al., 2016; Sullivan et al., 2018), however, it is rarely or sparsely measured (Kenzo *et al.*, 2009), due to the dense and multi-layered structure of tropical forests (Hunter *et al.*, 2013; Kearsley *et al.*, 2017). In addition, while H-D regressions for boreal and temperate forests have been well investigated (Lam *et al.*, 2017; Molto *et al.*, 2014), there is a shortage of such models for tropical forests due to operational constraints (Lam *et al.*, 2017). These challenges include the difficulty in tree height measurement even with the best conditions for measurement (Rennie, 1979; Michael

S. Williams, Bechtold, & LaBau, 1994), and forest conditions such as dense understory vegetation, tall canopies, and closed-canopy situations that reduce the line of sunshine (Hunter *et al.*, 2013). Moreover, tree height measurement in tropical forests requires both labour intensive work (Hunter *et al.*, 2013) and can result in potentially large errors (Hunter *et al.*, 2013; M. S. Williams & Schreuder, 2000).

Kearsley *et al.* (2017) pointed out that H-D regressions depend on a number of factors such as soil properties, light environment and surrounding effects, as well as location and stand types. They recommended the validation of H-D regressions in different eco-regions. Recently, Feldpausch *et al.* (2012) introduced a large number of H-D equations for pantropical forests at the continental and regional levels. They concluded that the application of specific regressions at regional levels could significantly decrease residuals in tree height estimation. In contrast, these equations cannot be easily applied at a local level for operational management and research (Lam *et al.*, 2017), as tree species and sites are not included in Feldpausch *et al.*'s (2012) models.

With many tropical forests, it becomes impractical and cumbersome to develop H-D models for each species. Some scientists have used genus and species as random effects to develop nonlinear mixed effects models for tree height estimation in tropical forests (Khoa, 2014; Lam *et al.*, 2017). Under this grouping strategy, tree species of the same genus would share similar life history, tree form, allometry, survival patterns and resource- use strategies. However, Lam *et al.* (2017) found that a hierarchical grouping strategy did not support these similarities. This may be due to inadequate resolution of estimates of random effects that performed clustering of 842 tree species to 295 genera. In addition, the limited number of species (only one) in 155 genera may be another possible explanation for the insufficient clustering.

Other scientists used an ecoregion classification approach to develop H-D models (Huang, Price, & J. Titus, 2000; Khoa, 2014), based on principles of ecologically-based forest management (Huang *et al.*, 2000; Vu Tan Phuong, 2010). In a study on the development of ecoregion-based H-D models for white spruce in boreal forests, Huang *et al.* (2000) concluded that the ecoregion approach allows for such analyses, capturing the unique patterns of individual ecoregions in H-D modelling development. As a result, selected models may provide more reliable projections on a regional scale, and avoid potential errors. A previous study on the development of H~D models for evergreen broadleaf forests in Vietnam was conducted for REDD+ programs (Khoa, 2014). The development of H-D in Khoa's study is based on a destructive method with a large number of tree species. However, graphical analyses showed large residuals in all models. This means that the conclusions of Huang may be true in the case of H-D models for a single species, but not in the case of multiple tree species models.

In recent years, classification by functional group has been widely used in growth modelling studies. Kariuki *et al.* (2006) used regeneration strategy and shade tolerance to group 117 subtropical rainforest tree species of north-eastern New South Wales, Australia into 5 functional groups. Similarly, Adame et al. (2014) and Masripatin (1998) used regeneration strategy and average maximum tree height as criteria for grouping species for studies regarding diameter growth performance and growth modelling. The former concluded that using tree functional groups based on these criteria could improve efficiency of models. The author also indicated that it is necessary to apply this approach in tree species grouping since the growth rates of trees in tropical forests vary widely and becomes impractical to develop one model for each species. In this line, diameter growth models were substantially improved based on functional groups in secondary tropical forests in Puerto Rico (Adame et al., 2014). As such, functional grouping is critical for growth and yield modelling, but there is limited information about H-D models using such grouping strategy.

There is an increasing concern for the reduction of emissions from deforestation and forest degradation (Huy, Poudel, Kralicek, et al., 2016; Huy, Poudel, & Temesgen, 2016). According to Article 13 of the Paris Agreement, a transparency framework to build mutual trust and confidence for action and support in activities such as national greenhouse gases inventories, national communication and biennial updated reports needs to be made (UN, 2015). Tranparency can be achieved by following the UNFCCC's guildelines on GHG inventory and appropriate data. As part of this concern and framework H-D models become critical, because height is measured less frequently than dbh, and both estimates are required in models predicting above-ground biomass. Such models are also expected to support the role of conservation, sustainable forest management and enhancement of forest carbon stocks (REDD+) in developing countries such as Vietnam. In fact, the UN-REDD Programme for Vietnam carries out REDD+ projects that have supported the development of allometric equations as a scientific basis for more accurate biomass estimation of major natural forest types, especially evergreen broadleaf forests.

This chapter discusses such H-D models. It describes the construction of H-D models for different tree groups of evergreen broadleaf forests using data provided by the Forest Inventory and Planning Institution (FIPI) and the Vietnamese Academy of

Forest Sciences (VAFS). In addition, a validation of the H-D models is carried out and is also compared with other published models using independent datasets.

METHODS

Data preparation

In Chapter 2, data was separated by functional groups (DATA1) which is now used to develop H-D models.

Validation data for tree height models (hereafter called DATA2) were collected by the Research Institute for Forest Ecology and Environment (RIFEE) and the Silviculture Research Institute (SRI) under VAFS. RIFEE was responsible for data collection from 90 2500m^2 plots and 2 one-hectare plots in years 2011 and 2012 with financial support from the Japanese International Cooperation Agency (JICA) and the Vietnam UN-REDD Programme. In addition, data from 23 2500 m^2 plots were collected by SRI in 2012 in a national project entitled, "Research on silvicultural characteristics of main natural ecological systems in Vietnam". Trees with dbhs lower than 5.9 cm and the same categories presented above for DATA1 were also excluded from DATA2. The same tree species functional groups were used for analyses of DATA1 and DATA2.

Tree height – dbh model and validation

An exploratory analysis of DATA1 by region, family, and genus was also used to check whether there were any potential random effects including eco-region, species family and genus on the H-D model. There were no clear evidence of the effects, thus models without random effects were used to develop H-D models in this study. Several H-D models previously used in tropical forests (**EQ 3.1 to EQ 3.5**) (Feldpausch *et al.*, 2011; Khoa, 2014; Vibrans, Moser, Oliveira, & de Macneiro, 2015) were tested in this chapter:

Conditioned Weibull $H = 1.3 + a * [1 - exp[(-b * dbh^{\wedge c}]$ (EQ 3.1)

Parabola $H = a + b * dbh + c * dbh^2$ (EQ 3.2)

Hyperbola $H = a + \frac{b}{dbh} + \frac{c}{dbh}$ (EQ 3.3)

Conditioned Hyperbola $H = 1.3 - \frac{b*dbh}{(dbh+1)} + c * dbh$ (EQ 3.4)

Weibull $H = a * [1 - exp(-b * dbh^{\wedge c}]$ (EQ 3.5)

Where:

H = Tree height in meter

dbh = Diameter at 1.3 m outside bark in centimetres

a, b, c = equation coefficients

exp(x) = e^x, where e is the base of the natural logarithm

Scatter plots of nine extracted tree species showed outliers and potential linear relationships, and so a linear form was also used to develop their equations.

Linear H = a + b* dbh (EQ 3.6)

To select the optimal H-D models, the Akaike information criterion (AIC) and residual standard error (RSE) were used, which provide sufficient evidence of a statistical fit for the best regressions of mixed tropical forests (J. Chave et al., 2005; Kearsley et al., 2017). In addition, graphical residual analyses were applied to assess the variation of models and check for bias and for normality of residual distributions (Kearsley *et al.*, 2017).

$$AIC = n * log\left(\frac{SSE}{n}\right) + 2p \quad \text{(EQ 3.7)}$$

Where:

p is the total number of parameters in the equation and n is the sample size

SSE is the sum of squares of the residuals and n is the number of observations

$$RSE = \sqrt{\frac{1}{df}\sum_1^n (Y_i - \hat{Y}_i)^2} \qquad \text{(EQ 3.8)}$$

Where:

df: degree of freedom

Y_i: predicted value

$\hat{Y}_i$: Observed value

This study's best mixed species models, the model of Feldpausch *et al.* (2012) for pantropical forests in the Southeast Asia and the equations of Khoa (2014) for broadleaf forests in Vietnam, were applied to DATA2 for comparison. Mean absolute percent error (Basuki, van Laake, Skidmore, & Hussin, 2009; Huy, Poudel, Kralicek, et al., 2016; Huy, Poudel, & Temesgen, 2016) and the mean error or bias (J. Chave et al., 2005; Khoa, 2014) were used as criteria for the comparison. The models of the aforementioned authors are:

H = 57.122*(1 – exp(-0.0332*dbh^0.8468)) (Feldpausch *et al.* (2012) – EQ 3.9)

H = 1.3 + 38.055987*(1 - exp(-0.048622*dbh^0.807422)) (Khoa (2014) – EQ 3.10)

Where:

H: Tree height

dbh: Diameter at breast height

exp(x) = e^x, where e is the base of the natural logarithm

Mean absolute percent error (MAE%) and bias (S%) calculations are shown in EQ 3.11 and EQ 3.12.

$$\mathrm{MAE}(\%) = \frac{100}{n}\sum_{i=1}^{n}\left\{\frac{|Yi - \hat{Y}_i|}{\hat{Y}_i}\right\} \qquad \text{(EQ 3.11)}$$

$$S(\%) = 100 * \frac{\sum_{i=1}^{n}(Yi-\hat{Y}_i)}{\sum_{i=1}^{n}\hat{Y}_i} \qquad \text{(EQ 3.12)}$$

Where:

Yi: predicted value

$\hat{Y}_i$: observed value

n = number of observations

Finally, residual distributions were used for a final comparison of the mentioned tree height models, using validation data DATA2.

RESULTS

The outcome of mixed-effect H-D models for multi-species tropical forests in Vietnam is described in **Table 3.1**. Nonlinear forms including EQ 3.1, EQ 3.2, EQ 3.3, EQ 3.4, and EQ 3.5 were employed to develop H-D models for different groups extracted from DATA1, of which the EQ 3.1 and EQ 3.5 fitted well to the groups since the forms showed significant parameters, the lowest AIC and RSE, the lowest actual standard error (SE), and the smallest range of residuals. Coefficients of developed equations for seven tree species groups including group 1 (G1), group 2 (G2), group 3 (G3), group 4 (G4), group 7 (G7) and group 8 (G8) were significant at $p < 0.001$, while these parameters of group 5 (G5) and group 9 (G9) were significant at different levels. The projected height curves of EQ 3.1 and EQ 3.5 were the best fitting equations compared to the other curves (**Figure 3.1**). The selected H-D models of G1, G2, G3, G6 and G9 had similar residual characteristics presenting random patterns and bounding the zero line (**Figure 3.2**).

Table 3.1. Selected tree height-dbh models for different species groups.

Group	Model form	a	b	c	AIC	RSE
G1	EQ 3.5	55.5454^{***} (10.4556)	0.0473^{***} (0.0078)	0.5967^{***} (0.0189)	46645.12	2.5440
G2	EQ 3.5	41.0912^{***} (2.6251)	0.0632^{***} (0.0032)	0.6188^{***} (0.0106)	119330.5	2.6609
G3	EQ 3.1	53.1926^{***} (4.9437)	0.0393^{***} (0.0028)	0.6543^{***} (0.0139)	33591.51	2.8646
G4	EQ 3.1	52.8545^{***} (14.6360)	0.03454^{***} (0.008)	0.6926^{***} (0.0323)	11559.52	2.3659
G5	EQ 3.1	41.84274^{**} (15.2228)	0.03321^{***} (0.0093)	0.77344^{***} (0.0591)	3159.98	2.2384
G6	EQ 3.1	38.49930^{***} (9.7798)	0.04253^{***} (0.0084)	0.70172^{***} (0.0409)	7119.108	2.4177
G7	EQ 3.5	26.3885^{***} (2.3171)	0.0793^{***} (0.0040)	0.7550^{***} (0.0431)	6379.48	2.6062
G8	EQ 3.1	30.9836^{***} (6.5040)	0.0549^{***} (0.0071)	0.7371^{***} (0.0633)	2314.43	2.4448
G9	EQ 3.1	56.7949^{*} (23.1361)	0.0369^{**} (0.0131)	0.6051^{***} (0.0371)	10781.76	2.5892

Note: Significance levels are presented as: ***, $p < .0001$; **, $p < 0.01$; and *, $p < 0.05$. Numbers in parentheses are standard errors of equation coefficients.

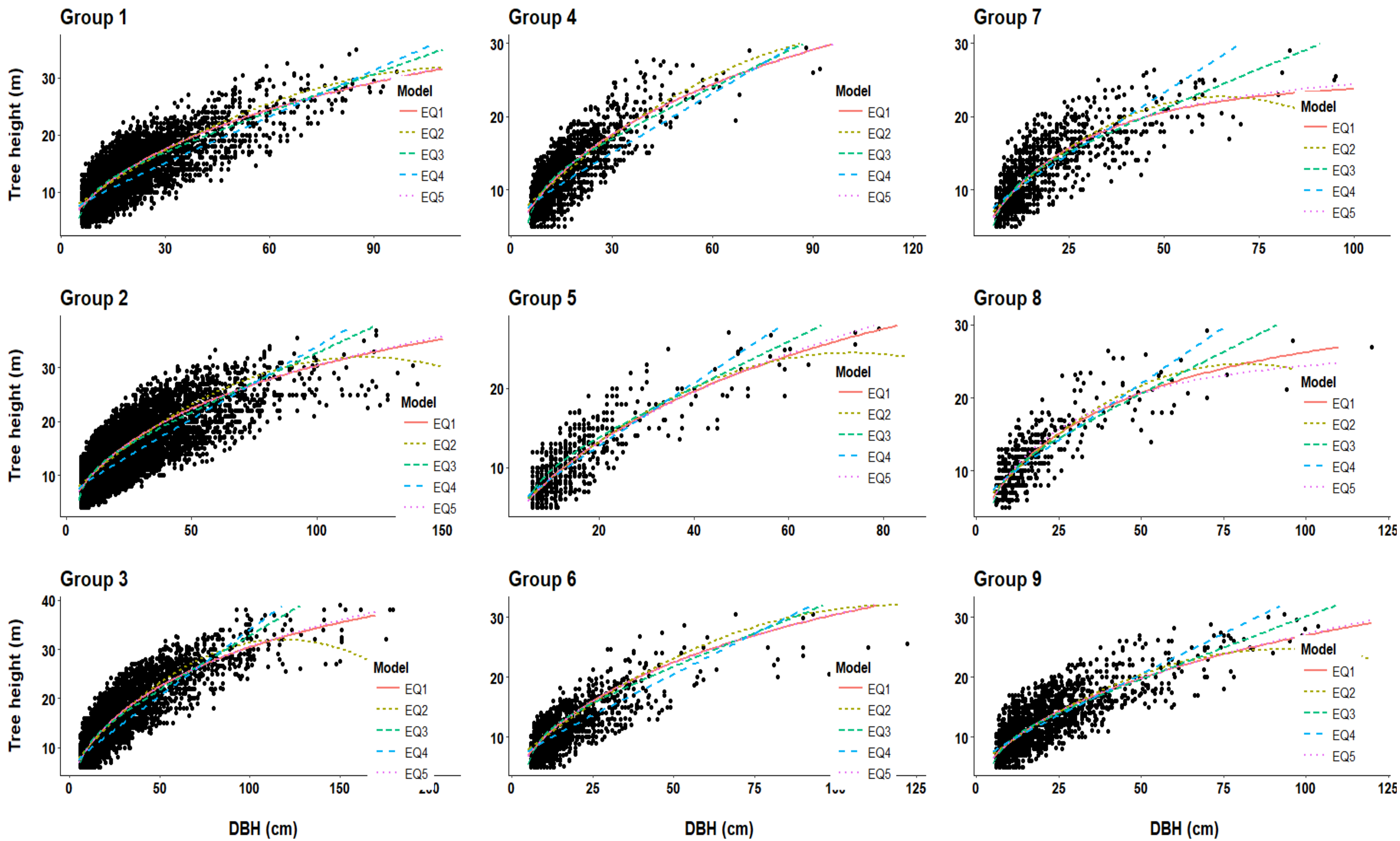

Figure 3.1. Relationship between tree height and dbh of the evergreen broadleaf forest by groups.

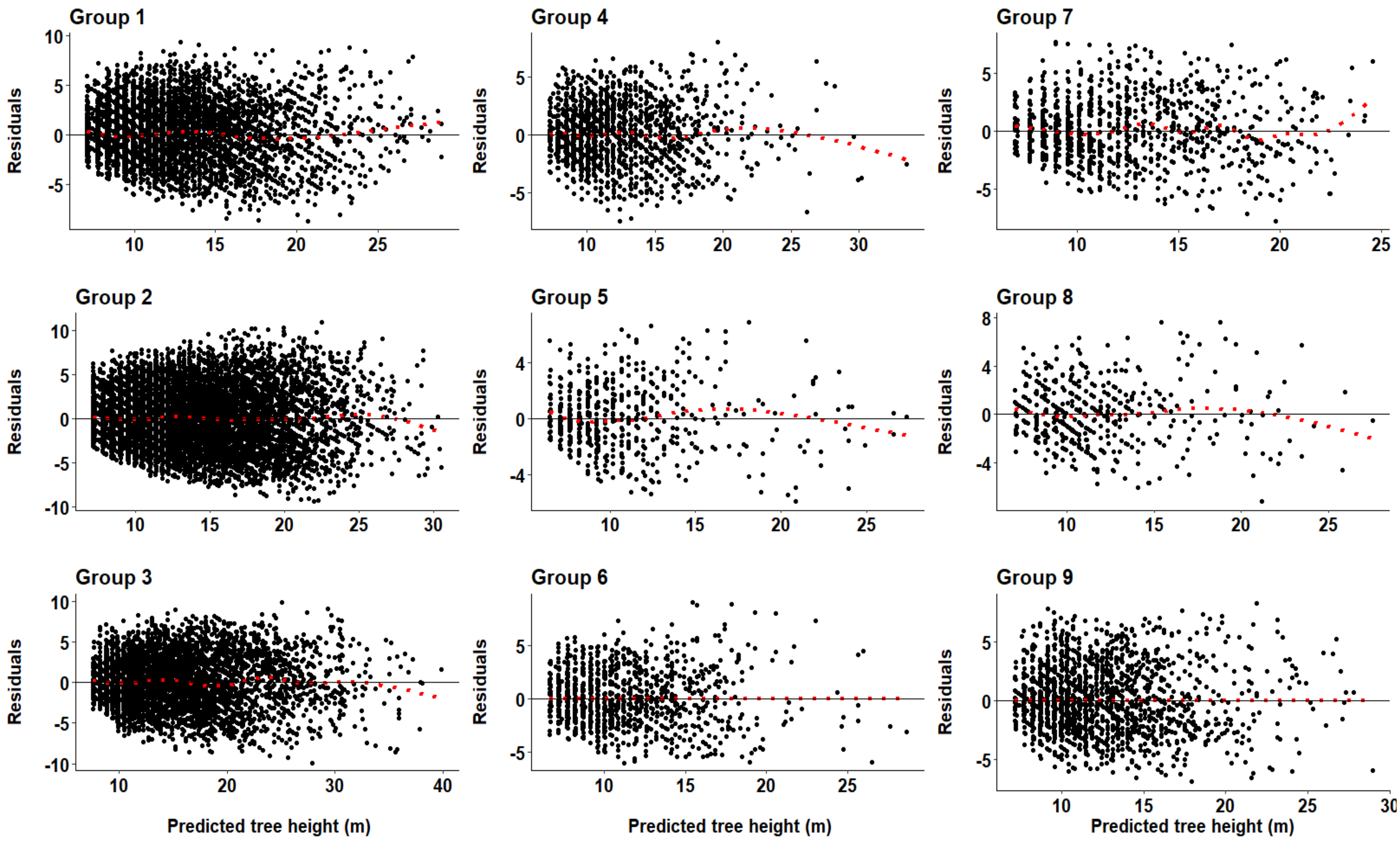

Figure 3.2. Residuals versus fitted values of tree height.

For those nine species that did not conform well to the H-D equations developed for each group, specific models were fitted (**Table 3.2)**. Both linear and non-linear H-D forms were selected depending on tree species.

Table 3.2. Selected tree height-dbh models for individual species that did not conform to the H-D models developed for each group.

Species name	N (tree)	Model form	a	b	c	AIC	RSE
Fokienia hodginsii	57	EQ 3.6	14.8257*** (2.5615)	0.2668*** (0.0258)	NA	274.99	2.6078
Celtis sinensis	42	EQ 3.3	14.7346*** (1.1832)	-60.5735*** (12.6429)	0.0327*** (0.0084)	214.63	2.5952
Ficus nervosa	93	EQ 3.1	28.2518*** (3.6717)	0.0583*** (0.0109)	0.7793*** (0.095)	473.21	2.8408
Caryodaphnopsis tonkinensis	146	EQ 3.3	18.5006*** (0.5774)	-98.4433*** (5.9244)	0.0450*** (0.0080)	630.01	1.9986
Sapindus mukorossi	23	EQ 3.3	13.6048*** (1.3780)	-46.1076* (17.8260)	0.0721*** (0.0142)	116.74	2.1261
Phoebe tavovana	64	EQ 3.3	15.3673*** (1.4842)	-61.3728*** (12.7493)	0.1065** (0.0356)	297.31	2.7622
Hopea hainanensis	1454	EQ 3.3	14.1854*** (0.7187)	-37.0624*** (4.2067)	0.2180*** (0.0273)	6661.65	2.4677
Scaphium macropodum	190	EQ 3.6	6.4821*** (0.3697)	0.4499*** (0.0149)	NA	913.40	2.6490
Dipterocarpus alatus	214	EQ 3.3	12.7605*** (0.8120)	-46.4622*** (6.9320)	0.2586*** (0.0146)	1088.41	1.1900

Note: Significance levels are presented as: ***, p < .0001; **, p < 0.01; and *, p < 0.05. Numbers in parentheses are standard errors of equation coefficients.

Since there were only 21 trees belonging to G8 in DATA2, the validation of the selected model for G8 was not implemented. The other eight H-D models of each group were compared with two given models introduced by Feldpausch et al. (2011) and Khoa (2014). Details are presented in **Table 3.3**. The bias and mean absolute errors of H-D models developed in this study were the lowest compared to those of EQ3.9 and EQ 3.10, except for the model fitted to data from VG7. The bias ranged from -14.0993% to 4.1832%, while the mean absolute errors were from 16.5286% to 30.3939%. In contrast, the statistical criteria of EQ 3.9 showed the highest bias and mean absolute errors in all validation data groups, ranging from 24.25% to 39.99% and 29.71% to 54.69%, respectively.

Table 3.3. Validation results using different tree height models based on dbh.

Validation data	Model form	N (tree)	S (%)	MAE (%)
VG1	**EQ 3.5**	2608	**4.1832**	**30.3939**
	EQ 3.9		39.9884	54.6839
	EQ 3.10		28.7628	48.1622
VG2	**EQ 3.5**	20694	**0.8111**	**26.1643**
	EQ 3.9		38.0630	50.3126
	EQ 3.10		25.5742	42.5830
VG3	**EQ 3.1**	938	**-8.8014**	**19.9743**
	EQ 3.9		27.8490	35.1511
	EQ 3.10		9.2970	23.3057
VG4	**EQ 3.1**	636	**-8.8817**	**21.4573**
	EQ 3.9		24.0966	33.63993
	EQ 3.10		10.7662	26.8205
VG5	**EQ 3.1**	144	**-11.8904**	**16.5286**
	EQ 3.9		29.7756	32.2667
	EQ 3.10		14.232	19.6266
VG6	**EQ 3.1**	1250	**-14.0993**	**22.1157**
	EQ 3.9		31.8420	41.1910
	EQ 3.10		16.6349	30.1927
VG7	EQ 3.5	421	-13.3513	19.0230
	EQ 3..9		24.4703	29.7113
	EQ 3.10		**8.1812**	**19.5327**
VG9	**EQ 3.1**	907	**-12.8957**	**24.1241**
	EQ 3.9		30.686	41.4771
	EQ 3.10		15.9199	32.0788

Note: N is the number of observations; VG1, VG2, VG3, VG4, VG5, VG6, VG7 and VG9 are validation data groups classified according to data DATA1.

Results of residual analyses showed that Feldpausch’s H-D model generated crucial overestimations for tree heights in 8 validation data groups available in this current study regardless of dbh size (**Figure 3.4**). Khoa’s model also presented significant overestimations in tree species of DATA2, but lower than the Feldpausch’s model. In contrast, residuals generated from selected H-D equations pointed out that there was an underestimation of tree height estimated by the equations in all tree species groups (**Figure 3.3**). Residual patterns of the developed equations also showed differences compared with those of fitted models (**Figure 3.4**).

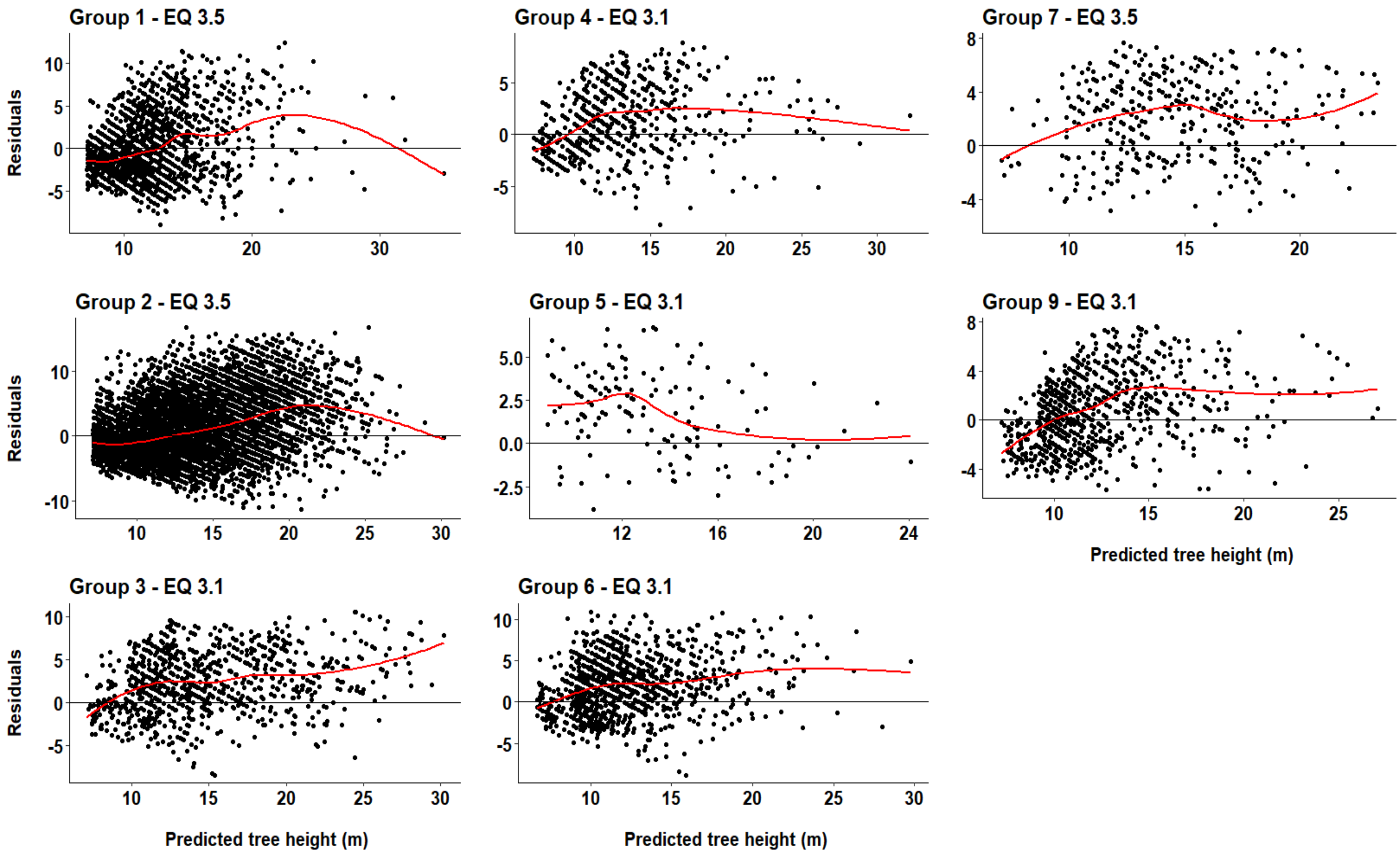

Figure 3.3. Residual vs tree height generated from fitted models in validation data.

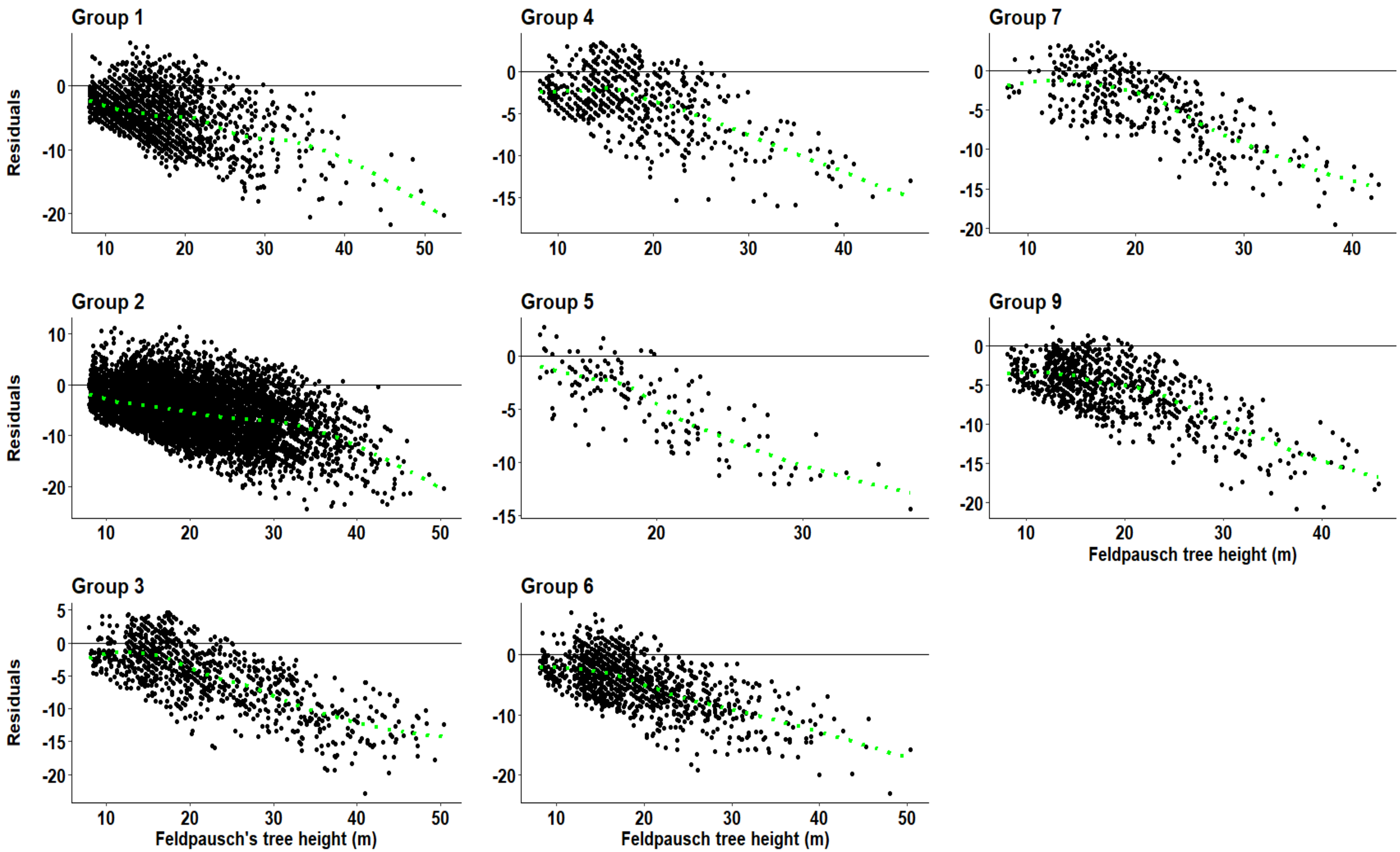

Figure 3.4. Residual vs tree height generated from Feldpausch's model in validation data.

DISCUSSION

Modelling H-D relationship using tree species groups in this current study eliminated heteroscedasticity and reduced residuals in the estimation of tree heights compared to models which were fitted without aggregating strategies (main species, family and genus groups, wood density groups, species groups by regions). Previous publications also indicated that species grouping enabled a crucial enhancement of the coefficient of determination of growth models (Phillips *et al.*, 2002). It was found that creating separate models for 9 species causing outliers was an appropriate approach for species grouping presenting lower RSEs. This resulted in a decrease of 3.385% and 5.366% in RSEs from EQ 5 of tree species group 2 (G2) (Species excluded: *Fokienia hodginsii*, *Celtis sinensis*, *Ficus nervosa*, *Caryodaphnopsis tonkinensis*, *Phoebe tavovana*, *Hopea hainanensis and Scaphium macropodum*) and EQ 3.1 of tree species group 3 (G3) (Species excluded: *Dipterocarpus alatus*), respectively. There was a minor change in RSEs of model EQ 3.1 of tree species group 1 (G1) (Species modelled separately: *Sapindus murkorossi*), reducing only 0.246% in RSEs compared with models tested without outliers removed from DATA1 in the exploratory analyses. The tree species groups generated from DATA1 might be used for tree growth modelling for mixed tropical broadleaf forests in Vietnam; however, the utility of these groups for growth modelling purposes would need to be examined in a separate study. In addition, in the context of tropical forests with high species diversity, updating new species into these groups and botanical identifications should be taken into account in future applications of species groupings (Phillips *et al.*, 2002).

This study developed H-D models for each species group in the forms of EQ 1 and EQ 5 for mixed broadleaf forests in Vietnam. The Weibull forms for H-D modelling were widely found in other studies to present the best fit (Wagle & Sharma, 2012). It provided more precise and less biased models (X. Zhang, Duan, Zhang, & Xiang, 2014), showed equally good fitting to tree height and dbh data (C. Peng, 1999), and performed better than other models including linear, hyperbolic, power, exponential, logistic, and Gompertz models (da Silva Scaranello et al., 2012). This study found that the slope coefficient of EQ 2.1 for species group G9 showed the lowest significance at $p < 0.05$ with the largest standard error (23.1361) compared to other models (**Table 3.1**). It was explained in **Chapter 2** that trees in G9 included species with missing information on the light demand, attainable size, and scientific name. Due to the lack of available information, these species were not properly aggregated into appropriate tree species groups. As a result, this group may comprise tree species with significantly different growth rates. Thus, these were probably the reasons why they have the lowest significance and the largest standard error. A comparison among the standard errors of model coefficients, AIC and RSE of EQ 3.5, and those of EQ 3.1 in G1, G2 and G7 was made. The results was that there were minor differences in AIC and RSE of the nonlinear forms. In addition, there were significant decreases in the standard errors in the developed models of EQ 3.1 compared to those of EQ 3.5. As such, for convenient application, this study recommended the use of the following H-D models of EQ 31 instead of selected models of EQ 3.5 for G1, G2 and G7, respectively:

H = 1.3 + 38.9069*(1 – exp(-0.0465*dbh^0.7039))(AIC = 46642.36, RSE = 2.5446; S = 4.988% , MAE = 29.55%) (EQ 3.1)

H = 1.3 + 33.0541*(1 – exp(-0.0545*dbh^0.7173)) (AIC = 119328.7, RSE = 2.6612; S = = 0.97%; MAE = 26.03%) (EQ 3.1)

H = 1.3 + 23.49942*(1 – exp(-0.06030*dbh^0.8568)) (AIC = 6378.55, RSE = 2.6073, S = -13.27%, MAE = 19.01%) (EQ 3.1)

In the result section, validation results for this study's models merely showed the lowest biases and mean absolute errors among the selected models, Khoa's model, and Feldpausch's, except for the results in the validation data for G7. On the other hand, Feldpausch's model showed the largest biases and MAEs compared to Khoa's and this study's models (**Table 3.3**). This trend can be seen in a number of previous studies when ecologists tried to compare their local regressions with larger-scale models (Basuki et al., 2009; Hunter et al., 2013; Huy, Poudel, Kralicek, et al., 2016; Huy, Poudel, & Temesgen, 2016; Kearsley et al., 2017). This study found that residuals generated from each tree species group to fitting data (DATA1) and validation data (DATA2), showed different trends (**Figure 3.2 and Figure 3.3**). This means that there could be some reasons from both DATA1 and DATA2 that may affect the accuracy of developed models and validation results.

The tree data for the development of H-D models in the current study was collected through ground-based measurement methods. A previous study revealed that tree height measured by traditional field-based survey was less accurate than direct measurement of felled stems (Sibona *et al.*, 2017). In addition, tree height measurement taken by field-based survey method in tropical forests is usually difficult. This is due to multi-layered, dense understory vegetation, tall canopies, and closed-canopy situations (Hunter *et al.*, 2013). As such, the measurement error may affect the accuracy of the developed H-D models. Different graphical analyses, which is based on stand characteristics, site conditions and climatic factors, were also used to examine residual patterns generated from validation procedure. Because of the rapid temperature rise (Houghton & Intergovernmental Panel on Climate Change. Working Group, 2001) and the potential of 3.4% global average increase in precipitation per 1^0C temperature rise (Allen & Ingram, 2002), it is therefore important that models should include climatic indicators in the assessment of forest growth (Raich, Russell, & Vitousek, 1997; Tyler, Macmillan, & Dutch, 1995). In the case of warming to 1.5^0C above pre-industrial levels (IPCC, 2018), it is especially important to assess and predict forest growth in the future.

Moreover, it was also recorded that the effect of site conditions on forest growth is critical in the development of forest management (Worrell & Malcolm, 1990). Thus, mean annual rainfall, elevation, temperature and solar radiation, stand density and stand volume, were used to explore whether these site conditions, climatic indicators and stand characteristics are affected by the validation results. However, there were no clear trends that are influenced by these conditions, indicators and characteristics on residual plots (**Figure 3.3** and **Figure 3.4**). This means that, though there were differences between two datasets DATA1 and DATA2 in terms of number of species in each group, the reasons explaining this phenomenon, however, were unknown. In the context of tropical forests, differences in sample sites between DATA1 and DATA2 for data collection may explain these trends.

The application of Feldpausch's model in local regions and specific sites is not particularly recommended in this study (Hunter *et al.*, 2013; Lam *et al.*, 2017). Although Khoa's H-D model was developed by a destructive method with a large number of trees, this equation applied to DATA2 produced an overestimation, although this was smaller than those found in Feldpausch's model. When Khoa's (2014) H-D model was applied to an independent dataset, it showed a bias of only -5.3985% (Khoa, 2014). One hundred and seventy-six trees species had a number of observation smaller than 4, and 48.5% of observations belonged to 6 main families among the 48 families recorded (Vu Tan Phuong, personal communication, April 20th, 2018). Due to high species diversity in tropical forests, model coefficients developed for species with limited numbers of observations would have a high variance and may be unreliable (Gourlet-Fleury *et al.*, 2005). This may explain the significant overestimation of Khoa's model.

Despite producing significant underestimates, this study's selected models used the nonlinear mixed effect approach that presented the lowest biases and MAEs with different validation data groups. The aforementioned discussion indicated that the recommended H-D models provided more accurate tree height estimation than Feldpausch's model. The aforementioned discussion indicated that the selected and recommended H-D models provided more accurate tree height estimation than Feldpausch's model specified for mixed tropical forests in countries in Southeast Asia and Khoa's model for the implementation of Vietnam's UNREDD+ program. It is therefore necessary to develop local and site-specific models for the estimation of tree height in tropical forests. These selected models for tree height estimation would be very useful in national forest inventories and REDD+ programs in Vietnam, which significantly reduce cost and time consuming in measurement due to the complexity of tropical forests.

CONCLUSION

The conditioned Weibull H-D function was the most suitable form in this study. A set of H-D models of different tree species groups in the form of the conditioned Weibull including G1 (SE = 0.06; bias ~ 4.98%), G2 (SE =0.02 ; bias ~ 0.97%), G3 (SE = 0.11; bias ~ -8.8%), G4 (SE = 0.13 ; bias ~ -8.88%), G5 (SE = 0.20; bias ~ -11.89%), G6 (SE = 0.09 ; bias ~ -11.10%), G7 (SE = 0.14; bias ~ -13.27%), G8 (SE = 0.17; bias ~ NA), and G9 (SE = 0.10, bias ~ 12.89%) was introduced to improve tree height estimation in broadleaf forests in Vietnam in UNREDD+ programs, greenhouse gas inventory, as well as national forest inventories. However, the range of dbh in each tree species group and botanical identifications should be considered in the inventories and programs.

As presented in **Table 3.3** and aforementioned discussion above, the estimation of tree height using the selected and recommended H-D models was less biased and more precise when applied to validation data than those of Feldpausch’s model and Khoa’s equation. However, a drawback of the selected models is that the residuals of the fitted models were still somewhat biased when tested against an independent validation dataset. Users may encounter some bias when applying these models in the field in tree height estimation, for reasons that this study has not been able to determine.

CHAPTER 4

BIOMASS AND BIOMASS INCREMENT OF EVERGREEN BROAD LEAF FORESTS

INTRODUCTION

Tropical forests store a large amount of carbon and play an important role in the global carbon cycle (S. Brown, 1997; Marshall et al., 2012; Ngo et al., 2013). At a global scale, they account for around 55% of the global forest carbon stocks and accumulate a significant amount of CO_2 from the atmosphere through the fundamental process of photosynthesis (Beer *et al.*, 2010; Grace, 2004). Because of their carbon storage potential, tropical forests are essential in mitigating the impacts of climate change (Locatelli *et al.*, 2015). However, during the last few decades, changes in global land use have resulted in the conversion of tropical forest to pasture and agricultural land, contributing an estimated 20% in the global carbon emissions (Badiozamani, 2007; Locatelli *et al.*, 2015).

Estimating aboveground biomass is the most important step towards quantifying forest carbon stocks, since carbon is approximately 50% of the total biomass (Basuki et al., 2009; J. Chave et al., 2005; Gibbs et al., 2007). There are several approaches to estimating carbon biomass storage. These include the biome-average approach, ground-based forest inventory data analysis, and remote sensing evaluation (Gibbs et al., 2007; Zhao, Guo, & Kelly, 2012). The biome-average approach uses representative values of forest carbon per unit area to be applied to broad forest categories. The second approach, based on forest inventory, comprises the measurement of diameter at breast height (dbh) and tree height, from which biomass and carbon stocks could be derived using individual tree biomass equations. The third approach involves the use of remote sensing imagery to derive indices such as the Normalized Difference Vegetation Index (NDVI) which can be converted to biomass and carbon stocks (Galidaki *et al.*, 2017; Pandapotan Situmorang, Sugianto, & Darusman, 2016). While these approaches seem straightforward, they must be combined with ground-based data to accurately estimate forest carbon (Drake *et al.*, 2003; Rosenqvist, Milne, Lucas, Imhoff, & Dobson, 2003).

Forest cover in Vietnam has changed drastically in the last eight decades. Forest cover was estimated at 14.3 million ha, equivalent to 43% of the total country area in 1943 (Jong, 2006). In the last 50 years, the forest area drastically decreased to about 9.2 million ha, or about 27.8% of the land area (Pham *et al*., 2012). The reasons behind the deforestation were mainly due to the Vietnam war that occurred from 1943 until the middle of the 1970s, as well as continued human activities such as agricultural expansion (FORMIS, 2005; MARD, 2010). Since the 1990s, the Vietnamese government has implemented various reforestation programs such as Program 327, Program 661, and the National Five Million Hectare Reforestation Program (5MHRP) to cope with deforestation and forest degradation (Pham *et al*., 2012). As a result, forest area increased by 4.1 million ha to 13.3 million ha that is equivalent to 39.1% of the total land area by 2009 (Pham *et al*., 2012).

Aboveground biomass is a key component in greenhouse gas (GHG) inventories carried out for the different forest categories set by the IPCC. The Ipcc (2003) encouraged countries to develop their country-specific emissions factors, such as allometric models for more accurate biomass estimation (Petrokofsky et al., 2012).

Biomass studies for natural tropical forests are critical for the implementation of REDD+ and other environmental mechanisms. They are still carried out, albeit at a small scale and in small numbers (T. V. Do *et al.*, 2018; Quynh & Hai, 2014; Vo Dai, Tran Van, Dang Thinh, Sato, & Kozan, 2015). In addition, researchers have only attempted to develop allometric equations for aboveground biomass estimation (Huy, Kralicek, et al., 2016; Huy, Poudel, Kralicek, et al., 2016; Huy, Poudel, & Temesgen, 2016). Thus, there is a gap in the existing studies on developing models for AGB and basal area increment of the forest, which is very important in REDD+ programs and national greenhouse gases inventories.

In the context of natural forests, site productivity is considered the main and most reliable indicator of site potential for timber or biomass accumulation or growth (Fu *et al.*, 2017). Site productivity, or site quality, is connected to the inherent ability of a certain site to grow trees or produce tree biomass. Site characteristics include soil, topography, and the climate of a forest area, which determine the site quality. The combination of: 1) soil depth, texture, and fertility; 2) slope, aspect, and elevation; and 3) precipitation, temperature and length of the growing season influences how well trees grow (DeYoung, Sutton, & BCcampus, 2016).

Many scholars argue that basal area increment can be considered a more reliable and useful indicator of site productivity than a stand height-based index (Berrill & O'Hara, 2014; Pokharel & Froese, 2009). Forest biomass accumulation and increment are known to be influenced by soil structure, climate, nutrient availability, tree diversity and human activities (Velazquez-Martinez, Perry, & Bell, 1992; Wright, 2005; Zheng, Feng, Cao, Li, & Zhang, 2006). Any small changes in forest biomass could lead to global consequences for the carbon cycle, species richness, and climate change (Bonan, 2008).

At the individual tree level, explanatory variables including basal area, initial diameter at breast height, basal area of trees larger than the subject tree, location indicators and eco-sites have been recommended for modelling basal area increment (Pokharel & Dech, 2012). At the stand level, the growth in merchantable volume per hectare and year could be calculated by including explanatory variables such as environmental indicators, forest types, basal area by species categories per hectare, the number of trees after logging per species group, and logging intensity per species group (Cailliez, Alder, Food, & Nations, 1980). Directly adding environmental indicators such as climate, is considered as one of the best strategies for improving precision of growth models compared with traditional mensuration models (Woollons, Snowdon, & Mitchell, 1997). Overall, there are also other complicated and science-oriented approaches, which includes physiological models and hybrid models (Rachid Casnati, 2016).

The above mentioned discussion on these studies suggest that forest biomass in Vietnam, especially natural forests, is important. Thus, this chapter describes studies aimed to achieve the following objectives:

(1) to estimate aboveground biomass of the forest level across regions and disturbance levels, and

2) to develop AGB and G increment models at the stand level, comprising stand, soil and climatic variables.

METHODS

Data preparation

Aboveground biomass and the biomass increment were calculated based on DATA1, which was discussed in the previous chapter. Diameter at breast height and tree height were measured in 2005 and 2010. Missing individual tree heights were estimated using selected tree height models developed in Chapter 3. The tree height models are as follows:

$$Tree\ height = 55.5454 * [1 - Exp(-0.0473 * dbh^{\wedge 0.5967})] \quad \textit{(EQ 4.1)}$$

$$Tree\ height = 41.0912 * [1 - Exp(-0.0632 * dbh^{\wedge 0.6188})] \quad \text{(EQ 4.2)}$$

$$Tree\ height = 1.3 + 53.1926 * [1 - Exp[(-0.0393 * dbh^{\wedge 0.6543}] \quad \textit{(EQ 4.3)}$$

$$Tree\ height = 1.3 + 52.8545 * [1 - Exp[(-0.03454 * dbh^{\wedge 0.6926}] \quad \textit{(EQ 4.4)}$$

$$Tree\ height = 1.3 + 41.84274 * [1 - Exp[(-0.03321 * dbh^{\wedge 0.77344}] \quad \textit{(EQ 4.5)}$$

$$Tree\ height = 1.3 + 38.4993 * [1 - Exp[(-0.04253 * dbh^{\wedge 0.7017}] \quad \textit{(EQ 4.6)}$$

$$Tree\ height = 26.3885 * [1 - Exp(-0.0793 * dbh^{\wedge 0.7550})] \quad \textit{(EQ 4.7)}$$

$$Tree\ height = 1.3 + 30.9836 * [1 - Exp[(-0.0549 * dbh^{\wedge 0.7371}] \quad \textit{(EQ 4.8)}$$

$$Tree\ height = 1.3 + 56.7949 * [1 - Exp[(-0.0369 * dbh^{\wedge 0.6051}] \quad \textit{(EQ 4.9)}$$

Where:

Tree height: Height of individual tree in metres

dbh = Diameter at 1.3 m outside bark in centimetres.

Exp(x) = e^x, where e is the base of the natural logarithm

Data on wood density were collected from various sources for biomass estimation, using a given equation (EQ 4.10). The first source came from local botanic research work in Vietnam (Ho, 1999, 2001, 2003; Hop, 2002). In addition, this study collected wood densities worldwide from digital databases and related publications (Jerome Chave et al., 2009; Zanne et al., 2009). Wood density data was also provided by the Vietnamese Academy of Forest Sciences (VAFS). Using the selected equation, the wood density of individual tree species was selected for biomass estimation. If wood density of individual tree species was not available, then the average wood density at the genus or higher taxonomy levels was considered. If there was no information on wood density in the first or second option, the default value 0.5 was selected for any tree species. The proportions of wood densities at species level, genus level and default values were 79%, 20.5% and 0.5%, respectively.

Validation for AGB and G increment models was performed using an independent dataset hereafter called DATA3, which was collected from the Silviculture Research Institute (SRI) under the Vietnamese Academy of Forest Sciences (VAFS). SRI was responsible for data collection from 34 1-ha plots collected in 2007 and 2012 in a national project entitled, "Research on silvicultural characteristics of main natural ecological systems in Vietnam". Trees with dbhs lower than 5.9 cm and the same categories presented above for DATA1, were excluded from DATA3. The same tree species functional groups were used for analyses of DATA1 and DATA3. Height -diameter models (**EQ 4.1 to EQ 4.9**) selected in Chapter 2 were also applied to calculate individual tree height of missing data in both surveys.

There are several categories of evergreen broadleaf forests in Vietnam. Disturbance categories (Ngoc Le et al., 2016) were used in this study to calculate G and AGB for poor forest, medium forest and rich forest, which are closed to HDF, LDF and UDF, respectively:

1. Heavily disturbed forest (HDF): 10 < timber volume < 100 m^3 ha^{-1}. Forests are classified as HDFs if they are degraded due to human activities which leads to severe impacts on their canopy structure, productivity, and volume. There are 10- 30% of stems above the harvestable size that have been removed.
2. Lightly disturbed forest (LDF): 101 < timber volume < 200 m^3 ha^{-1}. LDFs are defined if past logging leads to the loss of 6 to 10% of stems above the smallest harvestable size (dbh = 40 – 50 cm).
3. Undisturbed forest (UDF): This forest type held a timber volume of standing trees between 201 and 300 m^3 ha^{-1}. UDFs are located in areas that show no evidence of damage from human activity.

The same environmental data (see **Table 2.1**, Chapter 2) was collected for both DATA1 and DATA3 at the plot level. Annual rainfall, air temperature, and monthly solar radiation were downloaded from the WorldClim database (http://www.worldclim.org/) at a resolution of 30 seconds of latitude and longitude. Site characteristics, soil physical and chemical properties were collected from the International Soil Reference and Information Centre (https://www.isric.org) with the resolution of 250 x 250 metres.

Biomass and biomass increment

Biomass estimation was based on a mixed random effect model for tree aboveground biomass in evergreen broadleaf forests of Vietnam (Huy, Kralicek, et al., 2016). This equation uses three independent variables including dbh, tree height, and wood density. Details of the equation are as follows:

$$AGB\ (kg) = 0.806438*((dbh\ (cm)/100)^2*H\ (m)*WD\ (g/cm^3)*1000)^{\wedge}0.92021 \qquad (EQ\ 4.10)$$

Where:

AGB: Aboveground biomass in kg

dbh: Diameter at breast height in cm

H: Tree height in m

WD: Wood density in g/cm^3

Biomass increment during the 5 years was estimated by calculating the difference in biomass for 2005 and 2010. Average annual increment per individual tree was calculated by applying the following equation (Clark *et al.*, 2001; T. V. Do *et al.*, 2018).

$$\Delta AGB = \sum_{i=1}^{n}(AGB_{stem\ i\ in\ 2010} - AGB_{stem\ i\ in\ 2005}) + \sum_{j=1}^{m}(AGB_{recruited\ stem\ j\ in\ 2010} - AGB_{recruited\ stem\ j\ at\ DBH=6\ cm}) \qquad (EQ\ 4.11)$$

Where: *n* is the number of trees recorded in 2005 and surviving in 2010, and *m* is the number of recruited stems.

Mortality and recruitment

The annual recruitment rate and mortality rate of trees ≥ 6 cm in dbh were calculated using EQ 4.12 and EQ 4.13, respectively (T. V. Do *et al.*, 2018; H. E. M. Nascimento & Laurance, 2002).

$$m = 1 - [(N_0 - N_m)/N_0]^{1/t} \qquad EQ\ 4.12$$

$$r = 1 - [(N_0 - N_r)/N_0]^{1/t} \qquad EQ\ 4.13$$

Where N_0 is the number of trees in 2005, N_m is the number of dead trees, N_r is the number of recruited stems, and t is the interval i.e. 5 years. The m and r were calculated for each plot, and then means were estimated using all plot estimates.

AGB and G increment modelling at the stand level

Explanatory variables for AGB and G increment modelling comprised the following:

(1) Stand variables in the 2005 survey (stand density, species richness, basal area and AGB),

(2) Climate data (mean annual air temperature, mean annual rainfall, mean annual solar radiation),

(3) Elevation, and

(4) Soil properties (depth to bedrock, soil organic carbon, bulk density, soil texture, cation exchange capacity, and soil pH in KCl).

The Box-Cox transformation (Box & Cox, 1964) approach was used to transform predictor and explanatory data to 1) correct differences in scale (de Maçaneiro *et al.*, 2016; Zar, 2010) and 2) have normally distributed predictor and explanatory data. However, G and AGB increment models using transformed data showed larger range of residual patterns than models using original data. As such, G and AGB increment models were developed based on the original data without transformation.

A decision tree approach was used to select the likely influential or relevant variables (Kazemitabar J, 2017) explaining AGB increment and G increment. The size of a tree was determined by using the complexity parameter value (CP), which is represented in the complexity parameter table. The row in the CP table included all the lowest errors with the fewest branches, which were identified as the optimal size of a tree (Liebchen, 2010).

There were three types of errors including relative model error (relerror), error estimated from a 10-fold cross validation (xerror), and the standard error of the xerror (xstd). Graphically, the size of a tree was also determined using the CP plot. Rpart function in R (Terry M. Therneau, 2018) was used for the decision tree and to select variables probably influencing AGB and G increment. The most likely variables were used as explanatory variables in a multiple linear model. Optimal models were selected by beginning with a maximal model and then reducing the model sequentially until all coefficients of the model were statistically significant ($p < 0.05$).

Finally, the validation process was performed based on DATA3 using the mean absolute percent error (MAE%) and bias (S%) statistics (see **EQ 3.11** and **EQ 3.12**, Chapter 3). In addition, graphical residual analyses were also used to assess the variation of models and to check for bias and normality of residual distributions (Kearsley *et al.*, 2017).

Data analysis

The number of species, number of stems, mean dbh, G, AGB, and AGB increment were calculated for each plot separately (146 plots) at both times 2005 and 2010. Since the number of stems and AGB data at stand level were not normally distributed, a paired sample Wilcoxon test was used to compare the means of stems and AGB. It was also used to identify whether or not the mean ranks of different variables at two points of times differ.

RESULTS

1. Tree species characteristics

The number of species and families between 2005 and 2010 remained the same. In total, 401 tree species and 81 families were recorded. The total number of stems in 2005 and 2010 was 93318 and 96700, respectively. The average stand density was 639 (±272) stems per hectare. The smallest stem had a dbh of 5.92 cm compared to the 310 cm of the largest tree. In the 2005 data, *Lauraceae* comprised 40 tree species with 10346 stems, followed by *Fagaceae* with 22 tree species and 7612 stems. Three species had fewer than 10 stems. Meanwhile, *Gironniera subaequalis* had 2526 stems, *Syzygium zeylanicum* possessed 2210 stems, *Canarium tramdenum* held 2083 stems, and *Lithocarpus elegans* contained 2076 stems. *Ficus fulva* and *Muntingia calabura* were the least abundant tree species, with a record of only 1 stem each.

Stem abundance and growth characteristics of the forest are described in **Appendix II**. The number of tree species per ha recorded in the 2005 census ranged from 3 to 101 (56±20) per ha, while those recorded in the 2010 census were between 3 to 103 (60 ± 21). In both censuses, the number of families ranged from 3 to 46 per ha (30±8 and 32±8 for 2005 and 2010, respectively). Meanwhile, the number of stems per ha in the 2005 census ranged from 180 to 1381 (639±272), compared with those from 187 to 1504 (663± 281) in the 2010 census. These indicated high variation in the number of stems per ha in both censuses. The plot mean dbh was from 10.10 to 43.45 in 2005 and 10.81 to 45.78 in 2010. Finally, basal area ranged from 2.5 to 68.69 m^2 ha^{-1} (24.80 ± 13.01) in the 2005 survey, and from 4.58 to 73.68 m^2 ha^{-1} (28.59 ± 12.95) in the 2010 survey.

Pair comparisons using the Wilcoxon test showed that the number of stems between the two surveys were significantly different ($p < 0.01$). Similarly, there were considerable discrepancies in G between 2005 and 2010 ($p < 0.01$), which indicated higher mean G in the latter census.

2. Recruitment and mortality

The description of recruited stems and dead stems is presented in **Appendix III**. From 2005 to 2010, the number of dead trees ranged from 1 to 167 stems ha^{-1} (53±3). Meanwhile, the number of recruited stems ranged from 6 to 353 trees ha^{-1} (96±4.69), which showed larger variations compared to dead trees. Most of the recruited stems belonged to only 0-20 cm dbh class (see **Figure 4.1**). Similarly, the number of dead stems belonging to the 0 -20 dbh class was also high; however, it was lower than those of the recruited trees, and approximately 75% of total dead trees. The number of dead stems and recruited stems were noteworthy ($p < 0.05$). The differences of AGB of dead trees and recruited trees were also substantial different ($p < 0.05$), indicating higher AGB of dead trees than that of recruited stems.

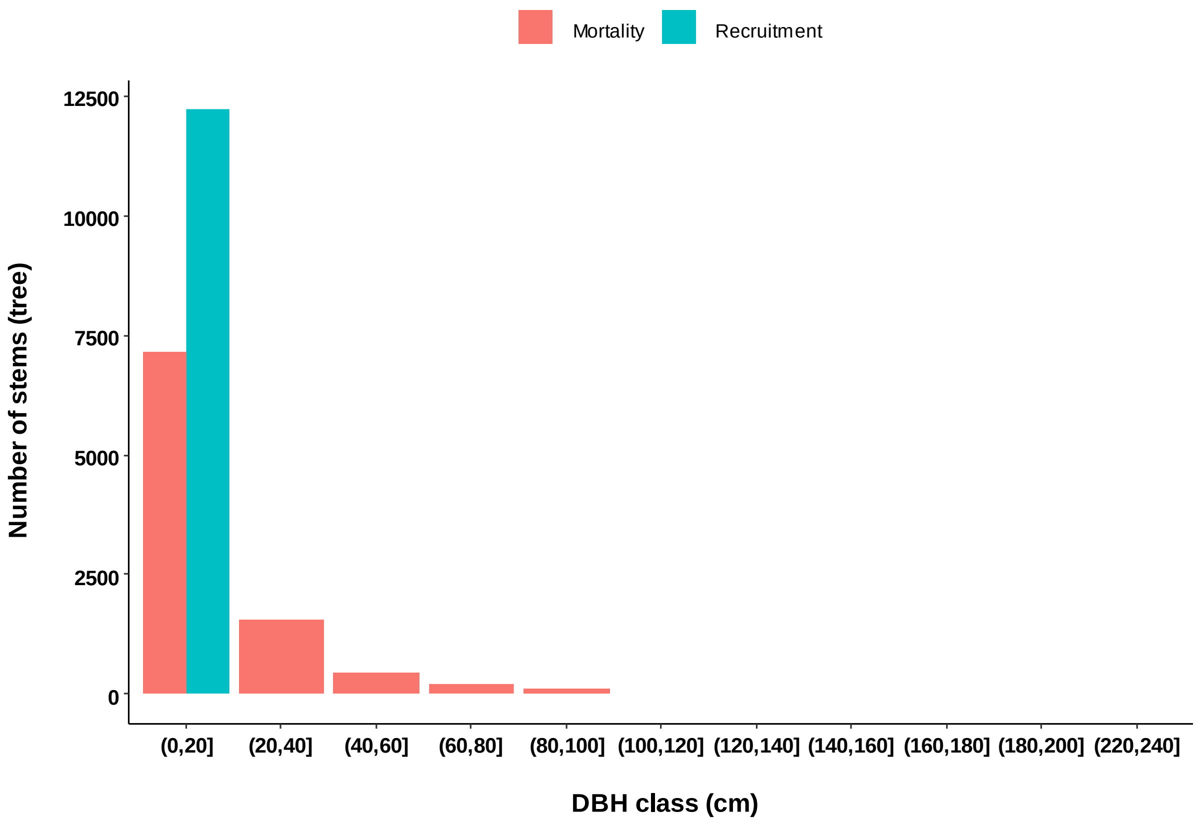

Figure 4.1. Distribution of the number of recruited stems corresponding to dbh classes for an interval of 5 years.

Annual mortality rate (0.018 ± 0.01), on a stem per hectare basis, was significantly lower ($p < 0.01$) than the recruitment rate (0.035±0.02). Similarly, there were statistically significant differences ($p < 0.001$) between the mortality rates on an AGB basis and the recruitment rates. Annual mortality rates in terms of AGB were higher than recruitment rates being 0.029 (±0.017) and 0.005 (±0.005), respectively (see **Figure 4.2**).

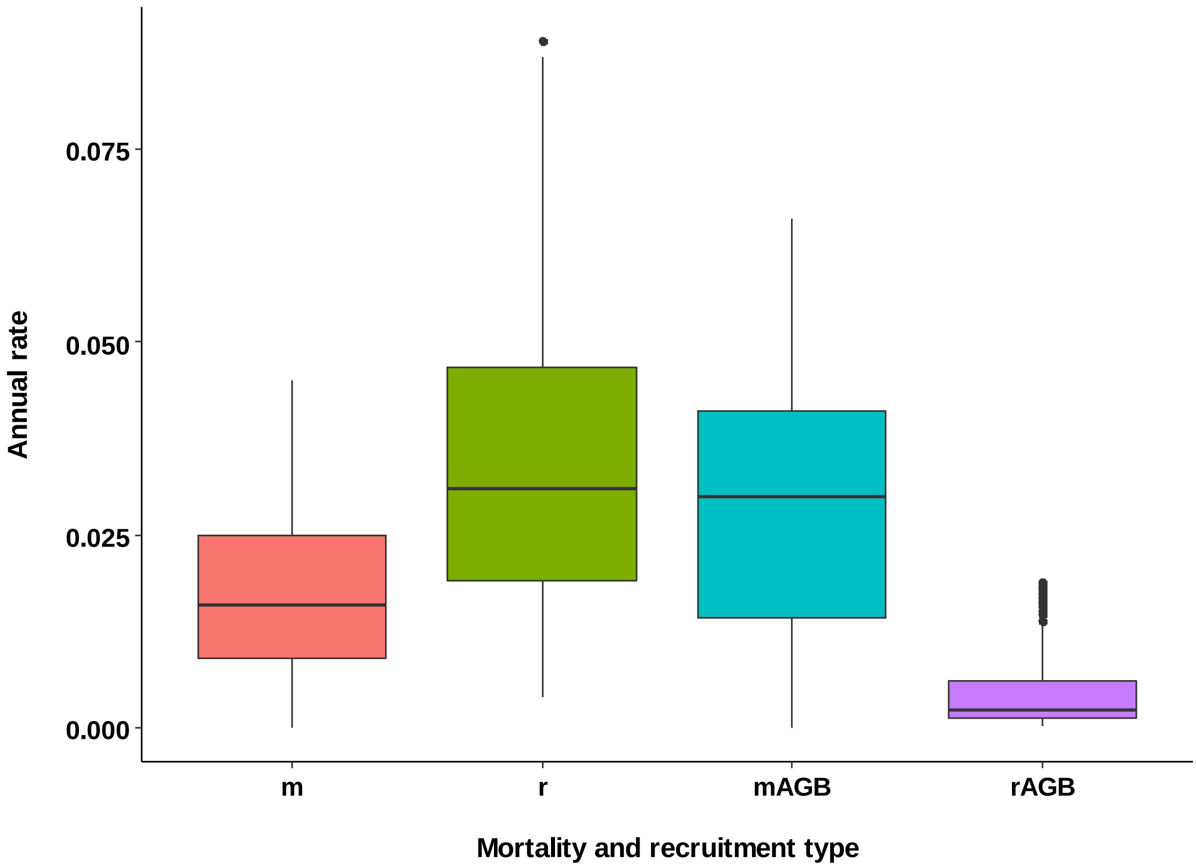

Figure 4.2. Annual mortality (m) and recruitment (r) rates, in terms of the number of trees per hectare and the aboveground biomass.

3. Basal area and aboveground biomass patterns

There was a wide range in the number of species between regions. The Northwest region exhibited the highest species richness with 276 species from 69 families. The North Central Coast region exhibited the second greatest diversity with 267 species and 63 families. In contrast, the Southwest region showed the lowest diversity with 90 species from 44 families. The average number of species and families per ha for each region are shown in **Table 4.1**.

The aboveground biomass of 146 permanent sample plots surveyed in 2005 and 2010 are presented in **Appendix II**. G in the 2005 survey ranged from 2.50 to 68.69 m^2 ha^{-1} (24.80 ± 13.01), while G in 2010 was generally greater than in 2005, ranging from 4.63 to 73.68 m^2 ha^{-1} (28.59 ±12.95). The AGB ranged from 12.92 to 651.68 ton ha^{-1} (174.97±114.95) in 2005 survey and from 27.79 to 719.11 ton ha^{-1} (204.56±117.38) in 2010. The average AGB increment from 2005 to 2010 was 32.16 (±12.08) ton ha^{-1}. The differences of AGB between 2005 and 2010 were statistically significant ($p < 0.01$).

The results for the biomass and biomass increment of each ecoregion in Vietnam are shown in **Table 4.1**. The lowest G was found in Northwest region being 17.54 ± 13.19 m^2 ha^{-1} in 2005 and 21.27 ± 13.49 m^2 ha^{-1} in 2010. Meanwhile, the highest G was found in the Central Highlands region in both 2005 and 2010. Consequently, the greatest AGB was also found in Central Highlands region being 250 ± 28.10 in 2005. The lowest AGB was found in the Northwest region (122.64 ± 128.15 ton ha^{-1}). In 2010, the highest and the lowest AGB were also found in the Central Highlands region (278.66 ± 27.53 ton ha^{-1}) and Northwest region (150.31 ± 138.50 ton ha^{-1}), respectively. The highest AGB increment over a period of five years was found in the South Central Coast region (39.85 ± 10.78 ton ha^{-1}), while the lowest in the Northeast region (23.36 ± 11.78 ton ha^{-1}). The AGB increment from 2005 to 2010 was positive for all regions ($p < 0.001$).

Table 4.1. Species richness, G, AGB, and G and AGB increments between 2005 and 2010 by ecoregion.

Region	No of PSPs (plot)	2005				2010				AGB increment (ton ha^{-1} $year^{-1}$)	G increment (m^2 ha^{-1} $year^{-1}$)
		No. species	No. families	G (m^2 ha^{-1})	AGB (ton ha^{-1})	No. Species	No. families	G (m^2 ha^{-1}; ±SE)	AGB (ton ha^{-1}; ± SE)		
CH	21	68±10	36±4	33.83±4.44	250.67±28.10	69±8	37±3	36.74±4.67	278.66±27.53	6.06±1.11	0.65±0.20
NCC	41	67±15	34±7	26.36±12.57	184.49±117.52	71±17	34±7	29.86±12.16	212.59±117.26	6.31±2.31	0.84±0.48
NE	12	41±12	26±7	23.3±16.66	148.39±115.15	46±10	27±7	26.44±17.19	169.89±117.52	4.67±2.36	0.74±0.46
NW	30	49±21	28±9	17.54±13.19	122.64±128.15	67±22	30±8	21.27±13.49	150.31±138.50	6.41±2.76	0.97±0.28
RRD	12	43±15	25±6	29.75±12.05	198.93±89.76	46±17	27±6	34.26±12.10	232±86.51	6.97±1.74	1.01±0.23
SCC	12	68±35	36±4	24.4±7.24	153.6±61.4	70±16	36±4	30.27±7.31	191.16±61.19	7.97±2.16	1.27±0.33
SE	9	36±21	23±12	22.18±16.91	183.36±171.82	35±20	23±12	26.35±16.85	218.12±172.64	7.29±3.60	0.89±0.50
SW	9	38±12	25±6	17.93±8.15	137.77±82.99	44±11	29±5	22.08±7.31	164.9±77.03	6.36±1.90	1.07±0.37

Ecoregions: NW: Northwest; NC: North Central Coast; NE: Northeast; CH: Central Highlands; SE: Southeast: SW: Southwest; RR: Red River Delta; SC: South Central Coast

There was a wide range of annual AGB and G increment within each region. The lowest G increment was found in the Central Highlands region, being 0.65 (±0.20) m^2 ha^{-1} $year^{-1}$. The highest G increment was 1.27 (±0.33) m^2 ha^{-1} $year^{-1}$ in the South Central Coast region. The lowest AGB increment was found in the Northeast region, being 4.67 (±2.36) ton ha^{-1} $year^{-1}$. In contrast, the highest AGB increment was found in the South Central Coast region, being 7.97(±2.16) ton ha^{-1} $year^{-1}$.

During a 5-year period, there were differences in the number of heavily disturbed, lightly disturbed and undisturbed plots, as well as differences in species and families. There was a reduction of 12 plots in the HDFs in 2005, which was merged in the LDFs in 2010. There were also 15 plots of LDFs in 2005 that were upgraded into the UDFs in 2010. Thus, undisturbed plots increased from 55 in 2005 to 70 in 2010. The number of species and families was the highest in UDFs, followed by LDFs, with the HDFs having the lowest number in 2005 and 2010 (see **Table 4.2**).

The lowest AGB was found in the HDFs, ranging from 12.92 to 98.52 tonne ha^{-1} (60.49 ±22.42) in 2005 and from 27.79 to 98.22 ton ha^{-1} (84.03 ±26.49) in 2010. UDFs showed the highest aboveground biomass, ranging from 201.08 to 651.68 ton ha^{-1} (289.26 ±99.66) in 2005 and from 204.89 to 719.10 ton ha^{-1} (317.72±102.23) in 2010. The highest annual basal area increment was found in the LDFs, followed by HDFs and UDFs. The annual AGB increment was the highest in LDFs with 7.63 ton ha^{-1} $year^{-1}$ (±2.67), and the lowest AGB increment belonged to HDFs with 5.46 ton ha^{-1} $year^{-1}$ (±2.15).

Table 4.2. General parameters of the permanent sample plots by timber volume stratification.

Item	HDFs		LDFs		UDFs	
	2005	2010	2005	2010	2005	2010
Number of 1-ha plot (plot)	44	32	47	44	55	70
Number of species	50 (±23)	56 (±24)	55 (±17)	59 (±19)	60 (±20)	63 (±19)
Number of families	28 (± 10)	30 (±10)	31 (± 7)	32 (±7)	32 (± 8)	33 (±8)
G (m^2 ha^{-1})	10.72 (±3.50)	14.43 (±4.10)	22.82 (± 3.83)	27.33 (±4.54)	37.75 (±10)	40.99 (±9.90)
AGB (ton ha^{-1})	60.49 (±22.92)	84.03 (±26.49)	148.38 (±24.99)	183.59 (±29.21)	289.26 (±99.66)	317.72 (±102.23)
G growth (m^2 ha^{-1} $year^{-1}$; ±SE)	0.96 (±096)		1.02 (±0.45)		0.73 (±0.28)	
AGB growth (tonne ha^{-1} $year^{-1}$; ±SE)	5.46 (±2.15)		7.63 (±2.67)		6.18 (±1.96)	

4. G and AGB modelling

Complexity parameter plots and the outcome of complexity parameter tables were represented in **Appendix IV**. It was found that the optimal size of the tree for the G increment model was 6, with the cp value of 0.029. Values of relerror, xerror, and xstd were 0.556, 0.899, and 0.110, repectively. In case of AGB increment model, the optimal size of the tree was 8 and the cp value was approximately 0.03. Three types of errors including relerror, xerror, and xstd were approximately 0.520, 0.933, and 0.128, repectively.

Basal area increment was better explained by stand density (Stems), mean annual rainfall (Rain), mean annual solar radiation (Srad), initial basal area (G05), and depth to bedrock (Brock) (see **Figure 4.3**). AGB increment was better explained by Stems, AGB in 2005 (AGB05), stand density (Stems), clay content (Clay), silt content (Silt), sand content (Sand), elevation, and soil organic carbon content (SOC) (see **Figure 4.4**). The G increment model included three independent variables (Solar, G05 and Rain) and three interactive effects (Srad×G05, Stems × Rain, Srad × Rain). There were five independent variables in the AGB increment model, including Stems, AGB05, Sand, Clay, Elevation, and four interactive effects (Stems × AGB05, Sand × Clay, Elevation × Silt, Sand × Elevation).

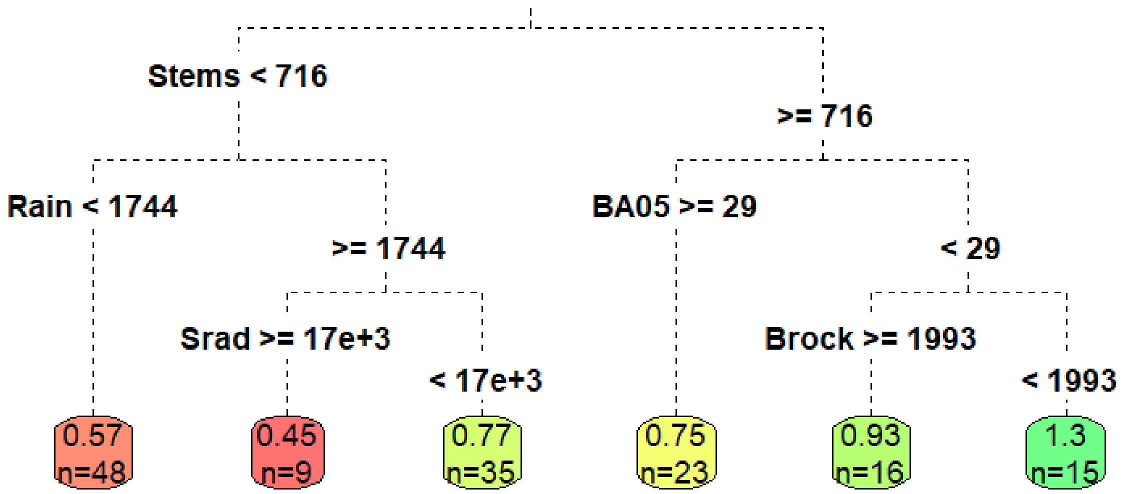

Figure 4.3. A pruned classification tree for G increment model, each node shows the predicted value and the number of observations.

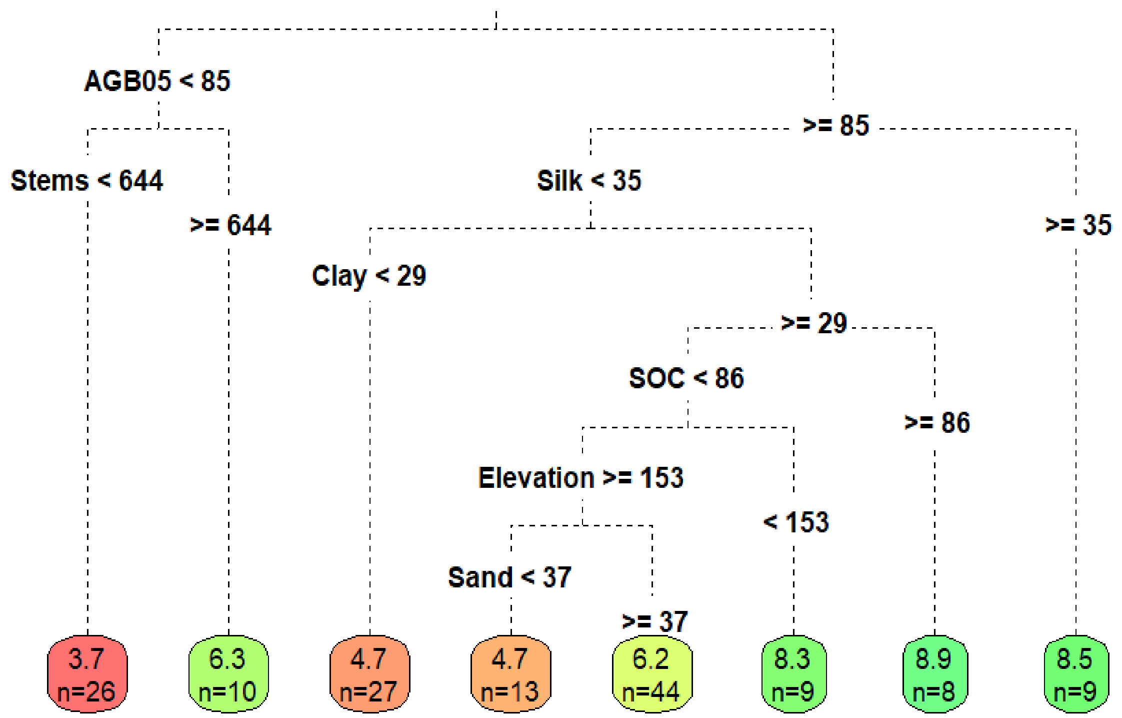

Figure 4.4. A pruned classification tree for AGB increment model, each node shows the predicted value and the number of observations.

Details of model coefficients are shown in **Table 4.3.** All coeficients of G increment model were statistically significant ($p < 0.01$ and $p < 0.001$), except the intercept. The AIC and RSE values were 94.41 and 0.324, respectively. Similarly, six coefficients of the AGB increment model were also statistically significant ($p < 0.001$). Residuals of the G increment model bounded the zero line, showing a better residual distribution patterns than the AGB increment model (see **Figure 4.5 and Figure 4.6**).

Table 4.3. Statistical summary of G and AGB increment models.

Type	Variable	Estimate	Standard error	P value
G increment model	Intercept	-4.18	1.21	0.00076
	Srad	0.0003	0.00007	5.54×10^{-5}
	G05	0.06	0.02	0.0010
	Rain	0.002	0.0006	0.0015
	Srad:G05	-4.083×10^{-6}	1.109×10^{-6}	0.0003
	Rain:Stems	4.279×10^{-7}	5.328×10^{-8}	3.67×10^{-13}
	Srad:Rain	-1.259×10^{-7}	3.460×10^{-8}	0.0004
AGB increment model	Intercept	41.52	11.11	0.0003
	AGB05	0.02323	0.004	4.76×10^{-8}
	Stems	0.008	1.144×10^{-3}	1.37×10^{-10}
	Clay	-1.382	0.3627	0.021
	Sand	-1.291	0.2774	7.65×10^{-6}
	Elevation	-0.0253	0.0096	0.0093
	AGB05:Stems	-3.423×10^{-5}	6.096×10^{-6}	1.06×10^{-7}
	Clay:Sand	0.043	0.009	9.04×10^{-6}
	Elevation:Silk	0.00036	1.557×10^{-4}	0.0228
	Sand:Elevation	0.004	1.382×10^{-4}	0.008

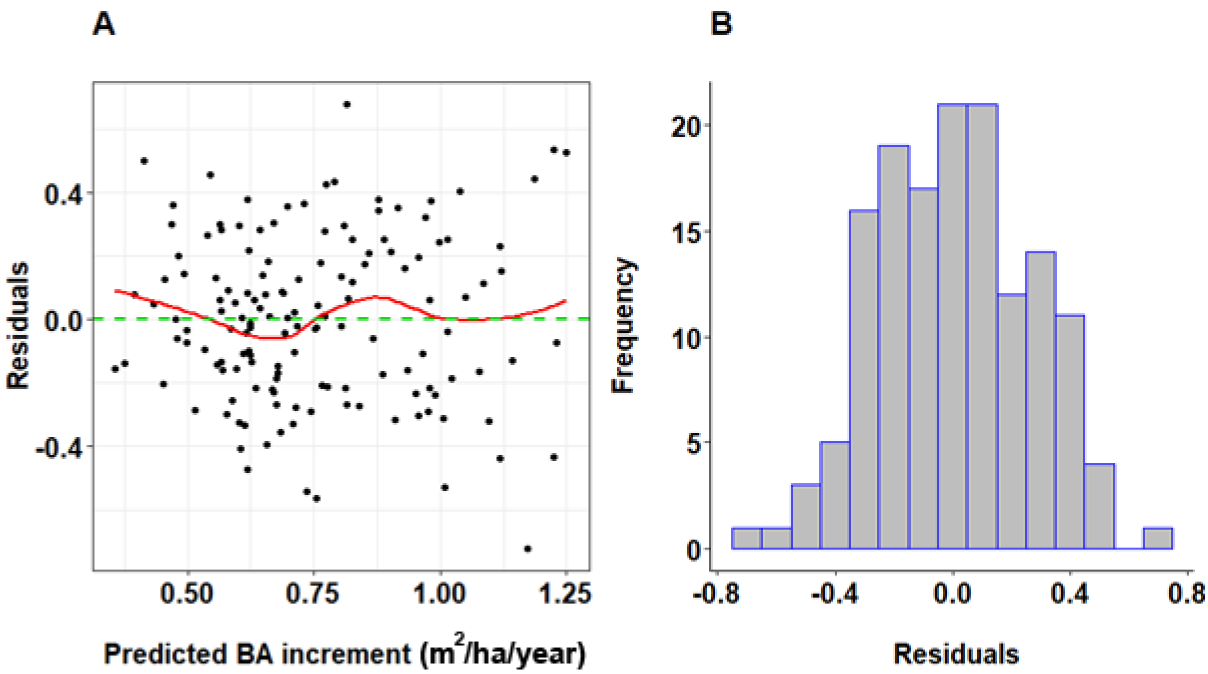

Figure 4.5. Residuals versus predicted values (A) and residual distribution (B) of G increment model.

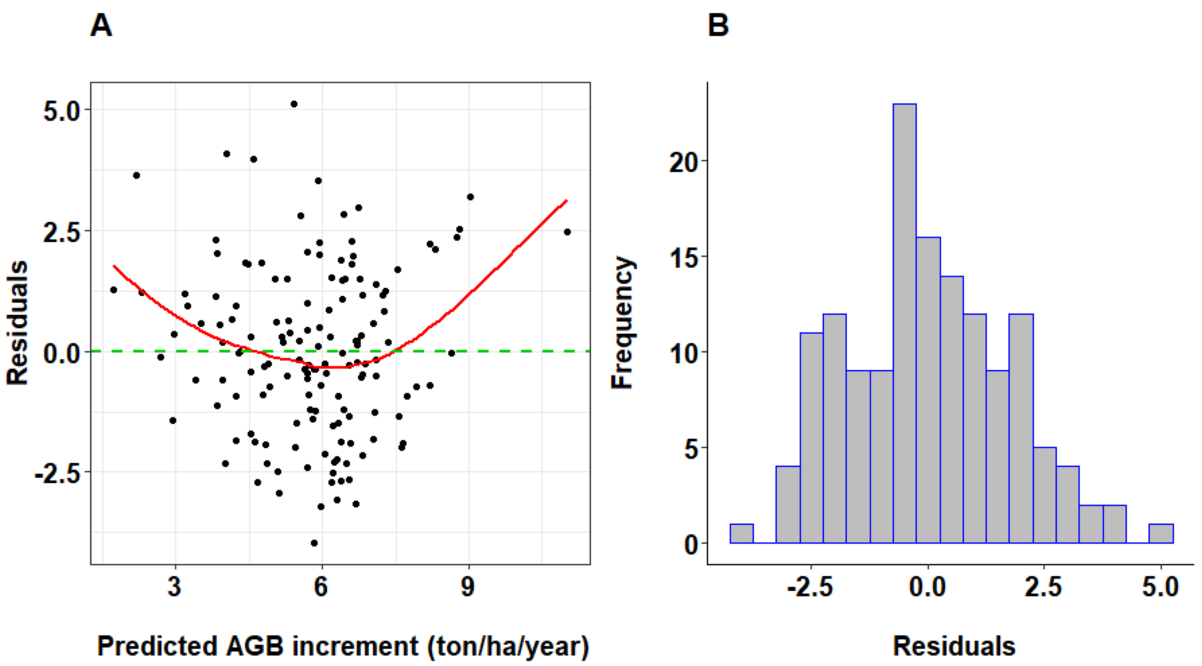

Figure 4.6. Residuals versus predicted values (A) and residual distribution (B) of AGB increment model.

The validation of the selected G and AGB increment models was based on DATA3, which included 17166 individual trees collected in 34 1-hectare PSPs (see **Appendix V**). Validation results showed that biases were ~ -4.30% and ~ 7.49% for G increment model and AGB increment model, respectively. MAEs, which measured the differences between validation data and predicted values generated from the selected models, were 26.91% for G increment model and 37.56% for AGB increment model. Bias distribution patterns by predicted G and AGB increment of evergreen broadleaf forests in Vietnam were represented in **Figure 4.7A** and **Figure 4.7B** below.

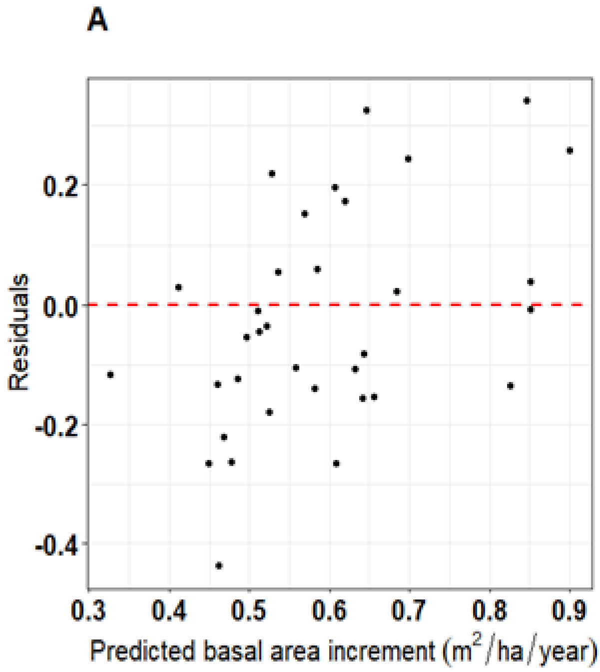

Figure 4.7. Bias versus predicted G increment (A) and bias versus predicted AGB increment of selected models using DATA3.

DISCUSSION

1. Tree species and families diversity

There was a crucial variation in the number of tree species and families among the PSPs (see **Appendix II**). This phenomenon can be attributed to the fact that PSPs were distributed in the whole country that were not under the homogeneous topographical conditions. A previous study revealed that a large variation of tree species was reported even in the homogeneous topographical forms (T. V. Do *et al.*, 2018), and the authors argued that species distribution and species diversity were significantly affected by micro-geographical tropics and edaphic environments.

This argument was also reinforced by other researchers (Moeslund, Arge, Bøcher, Dalgaard, & Svenning, 2013; C. Zhang *et al.*, 2016). The average numbers of tree species and families per site in this study were similar to those of the Lacandon rainforest in Mexico (59 ± 2 species; 28 ± 5 families) (Hernández-Ruedas *et al.*, 2014). In a previous study in Central Highlands region in Vietnam, it is concluded that the numbers of tree species and families were much lower than other tropical forests (T. V. Do *et al.*, 2018). For instance, there were 129 species in Eastern Ghats of Andhra Pradesh, India (Naidu & Kumar, 2016); 210 species in Pasoh, Malaysia (Kochummen, LaFrankie, & Manokaran, 1990); and 307 species in Amazonian Ecuador (Valencia *et al.*, 1994).

There were large numbers of species and families across the regions. The Central Highlands, North Central Coast, and South Central Coast regions showed higher diversity compared to other regions as previously discussed by (Van Do *et al.*, 2017;

Van & Cochard, 2017). The number of species and families in the Central Highland and the Northwest region (see **Table 4.1**) were much lower than in Do's studies on tropical forest in the same regions (81 ± 2 species and 35 ± 1 families; and 72 species and 33 families, respectively) (T. V. Do *et al.*, 2018; Van Do, Osawa, & Thang, 2010). In contrast, the same number of tree species (72) was also reported in a study on the structure of logged-moist forests in Huong Son, North Central Coast, Vietnam (Pham Quoc, 2008).

Although the species and families of the whole plots over a 5-year period remained unchanged, there was a trend that reveals an increasing number of species and families from HDFs to LDFs to UDFs (see **Table 4.2**). A previous study showed that the UDFs were relatively stable and were less (or not yet) influenced by human activities or natural disasters (Ngoc Le *et al.*, 2016). However, this study encountered increments in the number of species and families and aboveground biomass in the UDFs. This was also affirmed in Do's study mentioned above on the old-growth forests in Central Highlands region (T. V. Do *et al.*, 2018).

The increment characteristics of evergreen broadleaf forests under different types of forest stratification showed potential benefits in the implementation of REDD+ programs. These are regarded as possible sources of income through the national payments for environmental services and the national poverty reduction programs with the objective of strengthening biodiversity protection (Pham *et al.*, 2012).

2. Mortality and recruitment

Structures of forest ecosystems are defined by tree mortality and recruitment that are among the most important natural processes (Olvera-Vargas, Figueroa-Rangel, & Vázquez-LÓPez, 2015). The average annual rate of tree mortality in this study was 1.76% (see **Figure 4.2**), which was in the range of 1 – 2 % found in several other studies carried out in tropical forests (M. T. Nascimento, Barbosa, Villela, & Proctor, 2007; Olvera-Vargas *et al.*, 2015; Shen *et al.*, 2013). Lower stem mortality rates have been reported in other studies. For example, an old forest in Vietnam's Central Highlands had a 0.9% mortality rate (T. V. Do *et al.*, 2018) and the Kolli hills, Eastern Ghats, India had 0.73% mortality rate in a wet evergreen forest (Sundaram & Parthasarathy, 2002). With a range of 1 to 2% per year, the mortality rate eventually caused more than 50% reduction on the average stem age and a potential decrease in average tree size in a forest (Phillip *et al.*, 2009). Tree mortality rate in the present study was dependent on dbh classes, since more than 75% of dead stems belonged to dbh classes ≤ 20 cm (see **Figure 4.1**).

This result was supported by Do's research results in the Central Highlands. He found that more than 88% of dead trees belonged to the dbh classes ≤ 35 cm (T. V. Do *et al.*, 2018). However, the results of his research were contrary to other studies in Amazon forests and wet evergreen forest in India, where tree mortality was not dependent on stem sizes (M. T. Nascimento *et al.*, 2007; Sundaram & Parthasarathy, 2002). There were no human disturbances and abnormal natural phenomena recorded within 5 years. Thus, high mortality rates of stems smaller than 20-cm in dbh might be attributed to the low availability of sunlight in the understory (T. V. Do *et al.*, 2018;

Van Do *et al.*, 2010). There may also be other reasons that are common in tropical forests, such as diseases (T. V. Do *et al.*, 2018; Sturrock *et al.*, 2011), aging and other, unidentified factors which can cause the death of trees.

Studies of recruitment rate from tropical forests are scarce (Olvera-Vargas *et al.*, 2015). But typically, data from other studies for tropical forests showed that the recruitment rate usually ranged from 2 to 3% (Bin, Lian, Wang, Ye, & Cao, 2011; Olvera-Vargas *et al.*, 2015; Sherman, Fahey, Martin, & Battles, 2012). The results showed that the average recruitment rates of the evergreen broadleaf forest were higher than the range found in the study reported here (see **Figure 4.2**). This was in line with the annual recruitment rate of 3.17%, reported for subtropical monsoon forests in China (Shen *et al.*, 2013). This study's results are based on high annual recruitment rate in HDFs which contributed to nearly 30% of permanent sample plots (see **Figure 4.9**). The canopies of disturbed forests were severely impacted by past logging and other human activities (Ngoc Le *et al.*, 2016). Thus, the HDFs provided more growing space and light availability for recruited trees, which contributed to the high annual rate of forest recruitment.

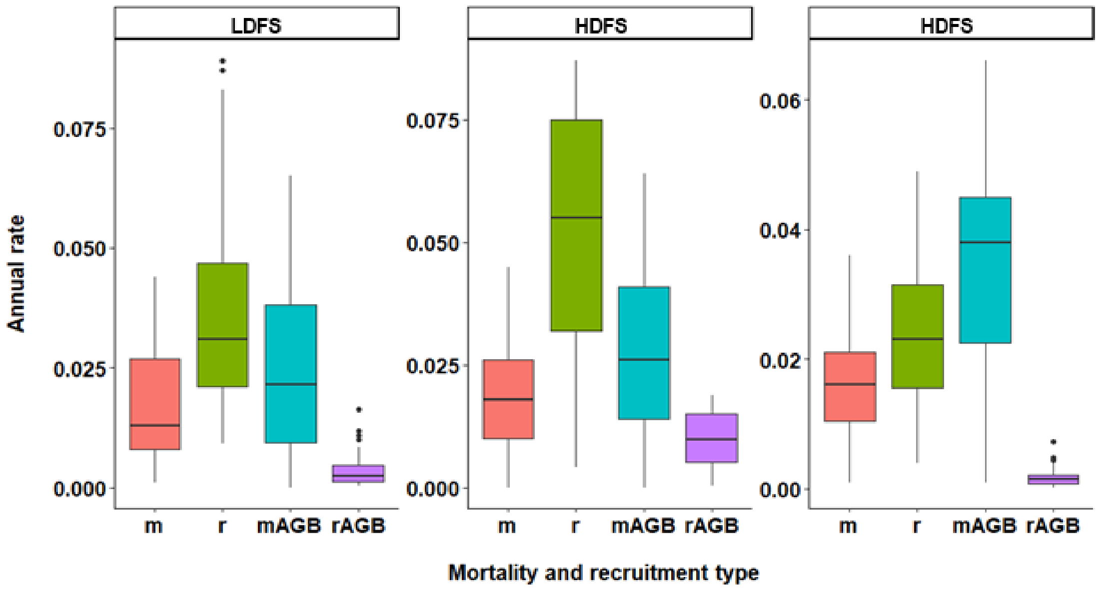

Figure 4.9. Annual mortality (m) and recruitment (r) rates, AGB mortality and recruitment rates by forest types.

3. AGB and AGB increment

AGB estimation is a crucial step linked to reducing carbon emissions from deforestation and forest degradation in developing nations (Gibbs et al., 2007; Hunter et al., 2013; Marshall et al., 2012). It can also be used as main carbon pools in land use, land-use change, and forestry (LULUCF) sector (USAID, 2013). In 2005, the mean AGB of forests across the whole country (see **Appendix II**) was slightly lower than the default value (180 ton ha^{-1}) introduced by IPCC for tropical moist deciduous forests in Asia (Paustian, Ravindranath, & Van Amstel, 2006). However, this study also found that the mean AGB was much lower than in other tropical forests, based on the following examples:

288 ton ha^{-1} in the Brazilian Amazon (Hunter *et al.*, 2013),

356 ton 398 ton ha^{-1} in the central French Guiana (Jérôme Chave *et al.*, 2008),

335 ton ha^{-1} in primary tropical forests in Singapore (Ngo et al., 2013),

256 ton ha^{-1} in Cambodia (Top, Mizoue, & Kai, 2004), and

300 ton ha^{-1} (estimated) in the Central Highlands, Vietnam (T. V. Do *et al.*, 2018).

The main reasons for the lower AGB of the forests in Vietnam may be forest degradation during the Vietnam war and deforestation from 1980 to 1990 when the country tried to rebuild and re-join the global economy (McElwee, 2015). At a regional level, there were large standard errors found in AGBs of most regions, except in the Central Highlands. This may lead to high uncertainty in emissions estimation of GHG projects in LULUCF. The AGBs of forest types classified by disturbed level were significantly different. The mean AGB of HDFs was much lower than secondary forest (140.7 ton ha^{-1}) in Seram, Indonesia (Stas, 2014), while mean AGB of LDFs was slightly higher than the secondary forest in Seram, but lower than the same forest type in Singapore (209.04 ton ha^{-1}) (Ngo et al., 2013). Similarly, undisturbed forests also showed lower mean AGB compared to other primary tropical forest (Ngo et al., 2013; Stas, 2014; Top et al., 2004). However, standard errors were relatively smaller than those of the mean AGB for the whole country and the AGBs estimated for different regions (see **Appendix II** and **Table 4.1**).

Some studies reported a decrease in AGB due to natural disturbances (M. T. Nascimento *et al.*, 2007; Rolim, Jesus, Henrique, Hilton, & Chambers, 2005). However, several findings revealed an AGB increment over a period of time (Baker *et al.*, 2004; JÉRÔMe Chave, RiÉRa, & Dubois, 2001; T. V. Do *et al.*, 2018; Vasconcelos, Zarin, Araújo, & Miranda, 2012). AGB increments at all levels in this study were much higher than the default value of 2 ton ha^{-1} $year^{-1}$ applied for tropical moist deciduous forests, which are more than 20 years old. However, they are smaller compared to the forests (9 ton ha^{-1} $year^{-1}$) that are greater than 20 years old in Asia (Paustian *et al.*, 2006). AGB increments of the forests in this study were also lower than AGB increment in the old-growth evergreen broadleaf forest (10.8 ton ha^{1} $year^{-1}$) in the Central Highlands of Vietnam (T. V. Do *et al.*, 2018). These indicated a large variation of AGB increment of the same forest type in different sites.

To date, most of the GHG sequestration estimates, which were used in GHG inventory programs, for Vietnam have depended on IPCC default emission factors. It is suggested that specific country-level emission factors could significantly improve estimation results and lead to a crucial change in the uncertainty of emission estimates (USAID, 2013). If the default emission factors such as AGB and AGB increment recommended by IPCC are applied to estimate GHG inventories and the Reference Emission Levels against which REDD+ emission reductions can be accounted for, then there will be high uncertainty in the estimates. Since there were large variations in the AGB of different regions and high standard errors of AGB at both national and regional levels, this study recommends that AGB and AGB increments of the evergreen broadleaf forests should be used in the future GHG inventories and REDD+ programs for higher accuracy in estimates.

4. G and AGB models

Rapid and significant influences on vegetation biomass due to environmental factors have already been discussed (Maherali & DeLucia, 2001). Furthermore, the effects of the number of stems and species on tree biomass were also investigated in previous studies (Bohn & Huth, 2017; Day, Baldauf, Rutishauser, & Sunderland, 2014; Slik *et al.*, 2010). However, understanding how ecosystems interact with the changes in environmental elements and tree diversity is one of the key challenges in ecology (Fyllas *et al.*, 2017). This recent study found that G increment was significantly associated with the mean annual solar radiation, the initial basal area/ha of previous inventory, and mean annual rainfall.

As of this writing, there is no known studies yet of G increment models that used these indicators as explanatory variables. However, there were strong correlations among net basal area ha^{-1} of forests, solar radiation, and annual rainfall located in New Zealand's Nelson region (Woollons *et al.*, 1997). Meanwhile, solar radiation was the climatic factor that most influenced forest productivity in the Amazon- Andes (Fyllas *et al.*, 2017). Since basal area/ha and forest productivity have a close relationship (Bohn & Huth, 2017; Nemani *et al.*, 2003), the effects of the initial basal area, solar radiation and rainfall on basal area increment were supported by research findings of these authors. Rainfall and solar radiation were found to be the most important indicators controlling the photosynthetic process of Amazon forests (Li, Xiao, & He, 2018), which directly influenced their growth. The inclusion of rainfall and solar radiation in G increment model of this study supported the past research of the abovementioned authors. These findings provide forest managers and policymakers baseline information on the relationship between G increment and the three mentioned explanatory variables, which may contribute to forest rehabilitation projects and REDD+ programs in Vietnam.

Various studies have examined the influences of forest stand, topography and soil properties on tree biomass. A study on forest biomass density across large climate gradients in the north of South America revealed that there was a weak correlation between AGB and environmental factors, especially with temperature (Álvarez-Dávila *et al.*, 2017). AGB was found to be positively linked with annual rainfall and clay-rich soils; and negatively associated with temperature, C:N ratio, and soil fertility (Lewis *et al.*, 2013). Key factors controlling biomass increment in the mid-subtropical forests of China were soil properties, topography and forest stand (Yin Ren Shanshan Chen Xiaohua Wei Weimin Xi Yunjian Luo Xiaodong Song Shudi Zuo Yusheng, 2016).

In this study, the selected AGB increment model was negatively correlated with clay content, sand content and elevation. Thus, the correlation pattern of elevation with AGB was supported by previous studies (Lewis *et al.*, 2013; Yin Ren Shanshan Chen Xiaohua Wei Weimin Xi Yunjian Luo Xiaodong Song Shudi Zuo Yusheng, 2016). However, clay content was found irrelevant in the study by Lewis *et al.* (2013). Stem density and its combination with initial AGB were found to be positively correlated with AGB increment, which is consistent with a previous study arguing that stem density was important for projecting forest biomass (Xu *et al.*, 2015). It was discovered that coefficients of all interaction variables in G increment models were small (see **Table 4.3**). The possibility that these interaction variables could be removed from the selected G increment model was examined. However, there was a high bias if three interaction variables were excluded from the model.

There are a large number of known factors that should account for the bias in regression models (J. Chave et al., 2005). The validation results showed that the predicted G and AGB increment differed by -4.30% and ~ 7.49%, respectively. It indicated that the G increment model tend to underestimate, while the AGB increment model shows a tendency to overestimate. It has been suggested that such models have a tendency to overestimate aboveground biomass (Madgwick & Satoo, 1975).

However, the overestimation by 0-5% was also found in the validation of AGB models for tropical forest (J. Chave et al., 2005).

CONCLUSION

Between two surveys, the number of species and families remained unchanged, 401 tree species and 81 families of the evergreen broadleaf forests were recorded. Annual mortality rate (0.018 ± 0.01) was lower than the recruitment rate (0.035±0.02). In general, this indicated that the forest was at the pre-climax stage, while the G and AGB are still being accumulated at high proportion. This may provide a more accurate information for Vietnamese forest policy makers to consider in forest management and protection.

The results in this chapter provided the information on G and AGB of evergreen broadleaf forests in Vietnam. The average G of the forests was 24.80 m^2 ha^{-1} (± 13.01) and 28.59 m^2 ha^{-1} in 2005 and 2010, respectively. The average AGB was 174.97 ton ha^{-1} (±114.95) in 2005 and from 204.56 ton ha^{-1} (±117.38) in 2010. It was found that G and AGB increment were the highest in South Central Coast, which was 1.27 m^2 ha^{-1} (±0.33) and 7.97 ton ha^{-1}, respectively. In regards to disturbance categories, the LDFs showed the highest G and AGB increment, which was 1.02 (±0.45) and 7.63 (±2.67), respectively. These results may provide useful information on G and AGB, particularly G and AGB increment for GHG and forest inventory in Vietnam.

The selected G increment model included four explanatory variables: solar radiation, initial basal area, annual rainfall, and number of stems per hectare (SE = 0.18, bias = -4.30%). Meanwhile, there were six indicators including initial AGB, number of stems per hectare, clay content, sand content, silt content and elevation involved in the final AGB increment model (SE = 1.69, bias = 7.49). Limited data for model validation may be considered as a drawback of this chapter. It is recommended that further validation with higher number of PSPs should be implemented.

CHAPTER 5

SYNTHESIS OF KEY FINDINGS

In conclusion, all the trees investigated were classified into nine different tree species groups (see Table 2.6). All tree species investigated in this study were shade-intolerant, shade-tolerant, and moderately shade-tolerant tree species. However, shade-intolerant species including three groups accounted for more than 72% of DATA1; therefore, in this study, they were used for analysing the relationship between environmental factors and tree species distribution. The study revealed that some environmental variables such as solar radiation, soil depth to bedrock, and clay content were strongly correlated to the species distribution of evergreen broadleaf forests in Vietnam. Three groups: G1 (Mean maximum attainable tree height: 33.53 m), G2 (Mean maximum attainable tree height: 21.94 m) and G3 (Mean maximum attainable tree height: 12.88 m), were significantly linked with solar radiation, soil depth to bedrock, and clay content. In addition, G1 and G3 were significantly correlated to the rainfall, not for G2. On the other hand, only G2 was associated with rainfall. In terms of solar radiation, the findings from this current study were in line with the findings of Satterlund and Means (1978), and Gates (1980). However, this differed from the conclusions made by Dorji et al. (2014) in their study. Meanwhile, the important role of clay content on species distribution was supported by the finding of Sarvade et al. (2016). And in regards to rainfall and temperature, this current study shared the same findings with Wright (2010) and Amissah et al. (2014).

This study resulted in H-D models, using H-D model forms used in previous studies (Feldpausch et al., 2011; Khoa, 2014; Vibrans et al., 2015) for tropical forests. The conditioned Weibull H-D function was the most suitable form in this research. The Akaike information criterion (AIC) and residual standard error (RSE) were employed to evaluate and select the best regression models. Graphical residual analyses were also used to examine the variation of models and to check for biases and for normality of residual distributions. The mean error or bias from Khoa's model and Feldpausch's model were then compared with those used in this study by using a validation procedure. Validation results showed that this study's models merely showed the lowest biases and mean absolute errors among the selected models, Khoa's model, and Feldpausch's, except for the results in the validation data for G7. The selected H-D models were as follows:

$$Tree\ height = 55.5454 * [1 - Exp(-0.0473 * dbh^{\wedge 0.5967})]$$

$$Tree\ height = 41.0912 * [1 - Exp(-0.0632 * dbh^{\wedge 0.6188})]$$

$$Tree\ height = 1.3 + 53.1926 * [1 - Exp[(-0.0393 * dbh^{\wedge 0.6543}]$$

$$Tree\ height = 1.3 + 52.8545 * [1 - Exp[(-0.03454 * dbh^{\wedge 0.6926}]$$

$$Tree\ height = 1.3 + 41.84274 * [1 - Exp[(-0.03321 * dbh^{\wedge 0.77344}]$$

$$Tree\ height = 1.3 + 38.4993 * [1 - Exp[(-0.04253 * dbh^{\wedge 0.7017}]$$

$$Tree\ height = 26.3885 * [1 - Exp(-0.0793 * dbh^{\wedge 0.7550})]$$

$$Tree\ height = 1.3 + 30.9836 * [1 - Exp[(-0.0549 * dbh^{\wedge 0.7371}]$$

$$Tree\ height = 1.3 + 56.7949 * [1 - Exp[(-0.0369 * dbh^{\wedge 0.6051}]$$

Where:

Tree height = Height of individual tree in metres

dbh = Diameter at 1.3 m outside bark in centimetres.

Exp(x) = e^x, where e is the base of the natural logarithm

The G increment model was influenced by four different environmental factors such as solar radiation, initial basal area, annual rainfall and the number of stems per hectare. The final AGB increment model involved more initial AGB, species richness and environmental variables than G increment model. The AGB increment model included variables such as initial AGB, number of stems per hectare, clay content, sand content, silt content and elevation. Species richness was not significantly correlated to either G or AGB increment models. Therefore, the hypothesis that the AGB increment was driven by the initial AGB, species richness and environmental factors was disproved. The standard errors and biases of the the G and AGB increment models were (SE = 0.18, bias = -4.30%) and (SE = 1.69, bias = 7.49), respectively. Details of the models are as follows:

$$BA_I = 0.0003 * SRAD + 0.06 * BA_i + 0.002 * RAIN - 4.083\ x\ 10^{-6} * SRAD * BA_i + 4.279\ x\ 10^{-7} * RAIN * STEMS_i - 1.259\ x\ 10^{-7} SRAD * RAIN - 4.18$$

$$AGB_I = 0.02323 * AGB_i + 0.008 * STEMS_I - 1.382 * CLAY - 1.291 * SAND - 0.0253 * ELEVATION - 3.423 * AGB_i + 0.043 * CLAY * SAND + 0.00036 * ELEVATION * SILK + 0.004 * SAND * ELEVATION + 41.52$$

Where:

G_I: Basal area increment (m^2 ha^{-1} $year^{-1}$)

G_i: Initial basal area (m^2 ha^{-1})

AGB_i: Initial aboveground biomass (ton ha^{-1} year^{-1})

$STEMS_i$: Number of stems in initial survey (stem ha^{-1})

SRAD: Mean annual solar radiation (kJ m^{-2} day^{-1})

RAIN: Mean annual rainfall (mm year^{-1})

ELEVATION: Elevation (m)

CLAY: Clay content (%)

SAND: Sand content (%)

SILK: Silk content (%)

There was a correlation between the selected environmental factors of tree species distribution. These data may be valuable in appropriate species selection for reforestation and rehabilitation programs in Vietnam. To be more precise, the selected environmental indicators for tb-RDA analysis of the chosen species groups could be used to determine the species which should be planted in specific regions.

The selected H-D models were found to be more precise and less biased than to Khoa's modela and Feldpausch's modela when applied to independent data. These models could be used to calculate tree height based on diameter at breast height. The application of the H-D models in the conditions of evergreen broadleaf forests may save time and labour costs. The model may significantly contribute to REDD+ projects, regional and national GHG inventory, and forest inventory programs in Vietnam.

The selected G and AGB increment models could be used to project G increment and AGB increment. However, another validation is highly recommended since these models were validated using data recorded for only 5 years. The application of these models with the involment of climatic, soil and stand variables may contribute to higher accuracy in the estimation of G and AGB sequestration than default factors introduced by the IPCC. In addition, the aforementioned models may provide basic background and relevant guidelines for forest managers in implementing appropriate policies for forest management and protection.

One of the limitations in this study was that it has not examined influences of topographic patterns on tree species distributions. There were no records of slope and aspect in the ecological permanent plots (EPPs). In addition, validation data for the selected H-D models collected by different organizations led to the underestimation of predicted values from the selected H-D models. Thus, future users of such models may encounter some bias when applying these in tree height estimation, for reasons that were not identifiable during this study. Lastly, although some climatic, soil and stand variables were included in the selected G and AGB increment models, hybrid physiological-mensurational models have not been tried, and they may improve the precision of the selected models in future.

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APPENDICES

APPENDIX I. Local name, scientific names, family names, abbreviation and maximum attainable height of tree species.

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
1	G1	Ba bet	*Mallotus paniculatus (Lam.)*	M.pan	15	SI	548
2	G1	Ba chac	*Euodia lepta (Spreng.) Merr*	E.lep	8	SI	13
3	G1	Ba dau	*Croton tiglium*	C.tig	12	SI	72
4	G1	Ba gac	*Rauvolfia verticillata (Lour.) Baill.*	R.ver	16	SI	60
5	G1	Bach benh	*Eurycoma longifolia*	E.lon	8	SI	145
6	G1	Bo an	*Colona auriculata*	C.auri	17	SI	286
7	G1	Bo cu ve	*Breynia fruticosa (L.) Hook. f.*	B.fru	18	SI	233
8	G1	Bo hon	*Sapindus mukorossi gaertn. F.*	S.muk	15	SI	41
9	G1	Boi loi la tron	*Litsea rotundifolia var oblongifolia*	L.rot	18	SI	39
10	G1	Boi loi nhot	*Litsea glutinosa (Lour.) C.B.Rob.*	L.glu	18	SI	1448
11	G1	Boi loi vang	*Litsea pierrei Lecomte*	L.pie	18	SI	151
12	G1	Bot ech	*Glochidion eriocarpum*	G.eri	10	SI	16
13	G1	Cam thi	*Diospyros maritima*	D.mar	18	SI	20
14	G1	Cap gai	*Capparis micracantha*	C.mic	6	SI	22
15	G1	Chac khe	*Dysoxylum binectariferum (Roxb.)*	D.bin	15	SI	107
16	G1	Chanh rung	*Atalantia citroides*	A.cit	10	SI	40
17	G1	Chap xanh	*Beilschmiedia percoriacea C.K. Allen*	B.per	17	SI	785
18	G1	Chay la to	*Artocarpus lakoocha Roxb*	A.lak	10	SI	242
19	G1	Cheo trang	*Engelhartia spicata*	E.spi	15	SI	240
20	G1	Co mai nhap	*Colona thorelii (Gagnep.) gagnep*	C.tho	16	SI	3
21	G1	Coc rao	*Cleistanthus petelotii Merr. ex Croiz*	C.pet	18	SI	92
22	G1	Com long	*Elaeocarpus limitaneus*	E.lim	10	SI	16
23	G1	Com tang	*Elaeocarpus griffithii (Wight) A.Gray*	E.gri	12	SI	690
24	G1	Cut sat	*Styrax annamensis Guill.*	S.ann	15	SI	148

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
25	G1	De trang	*Lithocarpus proboscideus*	L.pro	12	SI	1108
26	G1	Dom gai	*Bridelia balansae Tutcher*	B.bal	15	SI	17
27	G1	Dung san	*Symplocos laurina var.acuminata*	S.lau	14	SI	1227
28	G1	Goi nep	*Aglaia spectabilis (Miq.)*	A.spe	15	SI	1468
29	G1	Hoac quang	*Wendlandia paniculata (Roxb.) DC.*	W.pan	12	SI	152
30	G1	Hoi	*Illicium verum*	I.ver	8	SI	141
31	G1	Hoi hoa nho	*Illicium tenuifolium*	I.ten	10	SI	26
32	G1	Hoi nui	*Illicium difengpi*	I.dif	15	SI	15
33	G1	Hong bi rung	*Clausena dunniana*	C.dun	8	SI	109
34	G1	Hong rung	*Diospyros tonkinensis A. Chev.*	D.ton	14	SI	56
35	G1	Hu day	*Trema orientalis (L.) Blume*	T.ori	10	SI	324
36	G1	Ke duoi giong	*Markhamia caudafelina*	M.cau	15	SI	14
37	G1	Kha thu it rang	*Castanopsis ceratacantha ssp.semise*	C.cer	15	SI	35
38	G1	Le rung	*Pyrus pashia*	P.pas	12	SI	27
39	G1	Mang tang	*Litsea cubeba (Lour.) Pers.*	L.cub	10	SI	56
40	G1	Me rung	*Phyllanthus emblica L.*	P.emb	7	SI	28
41	G1	Mo	*Manglietia conifera Dandy*	M.con	15	SI	59
42	G1	Mo goi thuoc	*Actinodaphne cochichinensis H. Lec*	A.coc	15	SI	12
43	G1	Mo roi	*Litsea balansae Lecomte*	L.bal	6	SI	12
44	G1	Muong den	*Senna siamea*	S.sia	18	SI	50
45	G1	Muong truong	*Zanthoxylum avicennae (Lam.) DC.*	Z.avi	14	SI	250
46	G1	Ngai	*Ficus hispida L.f.*	F.his	12	SI	137
47	G1	Ngoa long	*Ficus fulva Reinw. ex Blume*	F.ful	10	SI	2
48	G1	Nho noi	*Diospyros apiculata Hiern*	D.api	16	SI	754
49	G1	Nhua ruoi	*Ilex cymosa Blume*	I.cym	15	SI	25
50	G1	Phuong do	*Delonix regia*	D.reg	18	SI	37
51	G1	Rang rang cambot	*Ormosia cambodiana*	O.cam	18	SI	156

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
52	G1	Rang rang ford	*Ormosia fordiana*	O.for	15	SI	41
53	G1	Rang rang la vai	*Ormosia semicastrata Hance*	O.sem	15	SI	5
54	G1	Re la day	*Cinnamomum cambodianum*	C.cam	17	SI	39
55	G1	Ruoi	*Streblus asper Lour.*	S.asp	15	SI	141
56	G1	Sam si	*Memecylon edule*	M.edu	16	SI	489
57	G1	Sen dao	*Photinia prunifolia (Hook. & Arn.)*	P.pru	15	SI	9
58	G1	So la nho	*Dillenia blanchardii Pierre.*	D.bla	15	SI	30
59	G1	So la to	*Dillenia hookeri Pierre*	D.hoo	15	SI	44
60	G1	Soi nui	*Lithocarpus silvicolarum (Hance)*	L.sil	15	SI	9
61	G1	Soi tia	*Triadica cochinchinensis Lour.*	T.coc	12	SI	882
62	G1	Soi trang	*Sapium sebiferum (L.) Roxb.*	S.seb	15	SI	51
63	G1	Tai chua	*Garcinia cowa Roxb. ex Choisy*	G.cow	16	SI	12
64	G1	Thanh ba	*Diospyros eryantha Champ*	D.ery	15	SI	2
65	G1	Thi rung	*Diospyros sylvatica*	D.syl	18	SI	1608
66	G1	Thich	*Acer tonkinense*	A.ton	12	SI	37
67	G1	Thu sam	*Dendropanax chevalieri (R.Vig.)*	D.che	10	SI	136
68	G1	Thung muc la to	*Holarrhena antidysenteria wall*	H.ant	12	SI	9
69	G1	Thung muc mo	*Wrightia laeris Hook.f.*	W.lae	10	SI	6
70	G1	Trau	*Vernicia montana Lour.*	V.mon	15	SI	195
71	G1	Trung ca	*Muntingia calabura*	M.cal	7	SI	1
72	G1	Trung ga	*Pouteria sapota (Jacq.)*	P.sap	18.3	SI	48
73	G1	Truong chua	*Nephelium lappaceum Blume*	N.lap	18	SI	1115
74	G1	Truong vai	*Nephelium melliferum*	N.mel	15	SI	1226
75	G2	Ba soi	*Macaranga denticulata (Blume)*	M.den	20	SI	1004
76	G2	Bang lang nuoc	*Lagerstroemia speciosa*	L.spe	25	SI	64
77	G2	Binh linh luc lac	*Vitex sumatrana var.urceolata*	V.sum	20	SI	232
78	G2	Bo de	*Styrax tonkinensis Craib ex Hartwich*	S.ton	20	SI	309
79	G2	Bong gon	*Ceiba pentandra*	C.pen	30	SI	8

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
80	G2	Bop long	*Actinodaphne pilosa (Lour.) Merr.*	A.pil	25	SI	317
81	G2	Bua nui	*Garcinia oliveri*	G.oli	30	SI	113
82	G2	Bua vang	*Garcinia xanthochymus Hook.*	G.xan	30	SI	402
83	G2	Buoi bung	*Acronychia pedunculata (L.) Miq.*	A.ped	20	SI	1121
84	G2	Ca duoi	*Cryptocarya cuneata BL.*	C.cun	20	SI	48
85	G2	Ca lo	*Caryodaphnopsis tonkinensis (Lecomte)*	C.tonk	20	SI	300
86	G2	Cam	*Parinari annamensis (Hance) J. E. Vidal*	P.ann	30	SI	110
87	G2	Cam lai	*Dalbergia oliveri*	D.oli	30	SI	16
88	G2	Cang lo	*Betula alnoides Buch.-Ham. ex D.Don*	B.aln	25	SI	11
89	G2	Canh kien	*Mallotus philippensis (Lam.) Mªll.Arg.*	M.phi	25	SI	15
90	G2	Chay	*Artocarpus tonkinensis*	A.ton	25	SI	129
91	G2	Chay la nho	*Artocarpus nitidus var.lingnanensis*	A.nit	20	SI	64
92	G2	Cheo	*Engelhardtia roxburghiana Wall.*	E.rox	25	SI	1237
93	G2	Chieu lieu nghe	*Terminalia triptera*	T.tri	25	SI	24
94	G2	Chieu lieu oi	*Terminalia corticosa*	T.cor	20	SI	5
95	G2	Cho dai	*Annamocarya sinensis (Dode)*	A.sin	30	SI	3
96	G2	Cho nhai	*Anogeissus acuminata (Roxb. ex DC.)*	A.acu	20	SI	25
97	G2	Choi moi	*Antidesma ghaesembilla Gaertn.*	A.gha	20	SI	269
98	G2	Chum bao	*Hydnocarpus ilicifolia*	H.ili	25	SI	91
99	G2	Co khiet	*Dalbergia hupeana Hance var. laccifera*	D.hup	20	SI	18
100	G2	Coc da	*Garruga pierrei Guill*	G.pie	30	SI	162
101	G2	Coc rung	*Spondias pinnata*	S.pin	20	SI	37
102	G2	Com cuong dai	*Elaeocarpus petiolatus (Jacq.) Wall.*	E.pet	25	SI	678
103	G2	Com la bang	*Elaeocarpus apiculatus*	E.api	25	SI	42
104	G2	Com la dao	*Elaeocarpus lanceifolius*	E.lan	20	SI	72
105	G2	Com la kem	*Elaeocarpus stipularis*	E.sti	30	SI	7
106	G2	Com trau	*Elaeocarpus sylvestris (Lour.) Poir.*	E.syl	22	SI	82
107	G2	Cong	*Samanea saman*	S.sam	30	SI	220

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
108	G2	Cong sua	*Eberhardtia tonkinensis Lecomte*	E.ton	25	SI	436
109	G2	Cong sua vang	*Eberhardtia aurata (Pierre ex Dubard)*	E.aur	22	SI	75
110	G2	Cong tia	*Calophyllum dryobalanoides*	C.dry	30	SI	603
111	G2	Cut ngua	*Archidendron balansae (Oliv.) l. Nielsen*	A.bal	23	SI	909
112	G2	Da ba gan	*Ficus nervosa*	F.ner	20	SI	166
113	G2	Da bo	*Prunus zippeliana*	P.zip	25	SI	11
114	G2	Da hop cach	*Manglietia dandyi (Gagnep.) Dandy*	M.dan	20	SI	45
115	G2	Da nau	*Chaetocarpus castanocarpus*	C.cas	25	SI	257
116	G2	Da qua vang	*Ficus hirta var.brevipila*	F.hir	20	SI	9
117	G2	Dai bo	*Archidendron tonkinensis I.Niels*	A.ton	20	SI	310
118	G2	Dai ngua	*Swietenia macrophylla*	S.mac	30	SI	26
119	G2	Dai phong tu	*Hydnocarpus anthelminthica*	H.ant	20	SI	151
120	G2	Dao	*Prunus persica*	P.per	25	SI	34
121	G2	Dau da dat	*Baccaurea sapida*	B.sap	25	SI	664
122	G2	Dau long	*Dipterocarpus baudii*	D.bau	30	SI	4
123	G2	Dau tra beng	*Dipterocarpus obtusifolius*	D.obt	30	SI	469
124	G2	De da	*Lithocarpus amygdalifolius*	L.amy	30	SI	10
125	G2	De do	*Lithocarpus elegans*	L.ele	25	SI	2174
126	G2	De gai	*Castanopsis chinensis (Spreng.)*	C.chi	25	SI	1296
127	G2	De gai An Do	*Castanopsis indica A. DC.*	C.ind	30	SI	367
128	G2	De gai nhim	*Castanopsis echinocarpa*	C.ech	30	SI	8
129	G2	De Sapa	*Quercus chapaensis*	Q.cha	25	SI	666
130	G2	De xanh	*Lithocarpus tubulosus*	L.tub	20	SI	574
131	G2	Den ba la	*Vitex trifolia L.*	V.tri	23	SI	297
132	G2	Den la rong	*Cleidiocarpon laurinum*	C.lau	20	SI	213
133	G2	Dinh	*Markhamia stipulata (Wall.) Seem.*	M.sti	25	SI	6
134	G2	Dinh thoi	*Fernandoa brilletii (Dop) Steenis*	F.bri	20	SI	16
135	G2	Do	*Rhamnoneuron balansae*	R.bal	22.6	SI	32

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
136	G2	Do ngon	*Cratoxylum formosum*	C.for	30	SI	93
137	G2	Dom long	*Bridelia monoica*	B.mon	20	SI	39
138	G2	Du	*Ulmus lancifolia*	U.lan	30	SI	8
139	G2	Dung che	*Symplocos cochinchinensis (Lour.)*	S.coc	30	SI	362
140	G2	Gao	*Bombax ceiba L.*	B.cei	25	SI	24
141	G2	Gao trang	*Anthocephalus indicus A.Rich.*	A.ind	30	SI	632
142	G2	Gao vang	*Adina cordifolia*	A.cor	30	SI	73
143	G2	Gioi la to	*Magnolia tiepii*	M.tie	20	SI	5
144	G2	Gioi vang	*Michelia champaca*	M.cha	30	SI	2
145	G2	Gioi xanh	*Michelia mediocris Dandy*	M.med	30	SI	579
146	G2	Goi te	*Castanopsis brevispinula Hickel et*	C.bre	28	SI	228
147	G2	Gu lau	*Sindora tonkinensis*	S.ton	30	SI	178
148	G2	Hoang dan gia	*Dacrydium elatum (Roxb.)*	D.ela	30	SI	292
149	G2	Hoang linh nam	*Peltophorum dasyrrhachis*	P.das	30	SI	5
150	G2	Huynh	*Tarrietia javanica*	T.jav	30	SI	220
151	G2	Ke	*Stereospermum colais*	S.col	20	SI	23
152	G2	Khao nhot	*Machilus leptophylla*	M.lep	28	SI	26
153	G2	Khao nuoc	*Phoebe pallida*	P.pal	26	SI	216
154	G2	Kien kien	*Hopea hainanensis*	H.hai	25	SI	1573
155	G2	Kim giao	*Podocarpus annamensis Gray*	P.ann	25	SI	11
156	G2	Ko nia	*Irvingia malayana*	I.mal	30	SI	122
157	G2	Lau tau	*Vatica cinerea*	V.cin	25	SI	172
158	G2	Leo heo	*Polyalthia thorelii (Pierre)*	P.tho	30	SI	1217
159	G2	Lim xanh	*Erythrophloeum fordii Oliv.*	E.for	25	SI	71
160	G2	Lim xet	*Peltophorum pterocarpum*	P.pte	25	SI	790
161	G2	Loi tho	*Gmelina arborea Roxb.*	G.arb	22	SI	81
162	G2	Long bang	*Dillenia turbinata Finet & Gagnep.*	D.tur	30	SI	201
163	G2	Long muc long	*Wrightia pubescens*	W.pub	20	SI	117

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
164	G2	Long nao	*Cinnamomum camphora (L.) J.Presl*	C.cam	20	SI	232
165	G2	Ma sua cao	*Helicia excelsa Blume*	H.ex	29	SI	112
166	G2	Man dia	*Archidendron clypearia (Jack)*	A.cly	20	SI	510
167	G2	Me	*Tamarindus indica*	T.ind	20	SI	4
168	G2	Me co ke	*Microcos paniculata L.*	M.pan	20	SI	527
169	G2	Mit ma	*Ficus vasculosa*	F.vas	20	SI	44
170	G2	Mo cua	*Alstonia scholaris (L.) R. Br.*	A.sch	30	SI	134
171	G2	Mo huong	*Cryptocarya chingii*	C.chi	20	SI	210
172	G2	Mo long	*Cryptocarya densifolia*	C.den	30	SI	104
173	G2	Mo lung bac	*Cryptocarya metcalfiana*	C.met	25	SI	168
174	G2	Mo vang	*Pachylarnax praecalva*	P.pra	30	SI	28
175	G2	Muong	*Cassia javanica subsp. nodosa (Roxb.)*	C.jav	20	SI	154
176	G2	Muong rang rang	*Adenanthera microsperma*	A.mic	25	SI	52
177	G2	Muong trang	*Zenia insignis Chun*	Z.ins	20	SI	2
178	G2	Muong xanh	*Albizia procera*	A.pro	25	SI	3
179	G2	My	*Lysidice rhodostegia Hance*	L.rho	25	SI	55
180	G2	Nang	*Alangium ridleyi King*	A.rid	25	SI	467
181	G2	Nanh chuot	*Cryptocarya concinna*	C.con	25	SI	377
182	G2	Ngat	*Gironniera subaequalis Planch.*	G.sub	20	SI	2621
183	G2	Ngat tron	*Gironniera cuspidata (Blume) Kurz*	G.cus	20	SI	122
184	G2	Nhoc	*Polyalthia cerasoides (Roxb.) Bedd.*	P.cer	20	SI	1317
185	G2	Nhoc la to	*Polyalthia lauii Merr.*	P.lau	20	SI	8
186	G2	Nuc nac	*Oroxylum indicum (L.) Kurz*	O.ind	21	SI	10
187	G2	Quao	*Dolichandrone columnaris Santis*	D.col	20	SI	80
188	G2	Que	*Cinnamomum cassia*	C.cas	20	SI	19
189	G2	Que Bac bo	*Cinnamomum tonkinensis*	C.ton	20	SI	200
190	G2	Quech tia	*Chisocheton cumingianus*	C.cum	30	SI	226
191	G2	Rang rang mit	*Ormosia balansae Drake*	O.bal	20	SI	420

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
192	G2	Rang rang xanh	*Ormosia pinnata (Lour.) Merr.*	O.pin	20	SI	970
193	G2	Re bau	*Cinnamomum bejolghota*	C.bej	25	SI	41
194	G2	Re gung	*Cinnamomum ovatum Lukman.*	C.ova	30	SI	1075
195	G2	Re huong	*Cinnamomum parthenoxylon (Jack)*	C.par	20	SI	878
196	G2	Re trang	*Phoebe lanceolata (Nees) Nees*	P.lan	20	SI	44
197	G2	Roi mat	*Garcinia ferrea*	G.fer	30	SI	41
198	G2	San thuyen	*Syzygium polyanthum (Wight) Walp.*	S.pol	30	SI	3
199	G2	Sang mau	*Horsfieldia amygdalina (Wall) Warb*	H.amy	25	SI	151
200	G2	Sang may	*Antheroporum pierrei*	A.pie	25	SI	442
201	G2	Sang ot ran	*Xanthophyllum colubrinum*	X.col	20	SI	150
202	G2	Sanh	*Ficus benjamina*	F.ben	30	SI	9
203	G2	Sao xanh	*Hopea helferi*	H.hel	30	SI	26
204	G2	Sau	*Dracontomelon duperreanum Pierre*	D.dup	20	SI	57
205	G2	Sen mu	*Shorea roxburghii*	S.rox	30	SI	299
206	G2	Seu	*Celtis sinensis*	C.sin	30	SI	85
207	G2	So	*Dillenia scabrella*	D.sca	30	SI	221
208	G2	So ba	*Dillenia indica L.*	D.ind	30	SI	67
209	G2	So khi	*Khaya senegalensis*	K.sen	30	SI	31
210	G2	Soi do	*Lithocarpus corneus*	L.cor	26	SI	31
211	G2	Soi phang	*Lithocarpus cerebrinus*	L.cer	25	SI	83
212	G2	Son huyet	*Melanorrhoea laccifera*	M.lac	30	SI	133
213	G2	Son ta	*Toxicodendron succedanea (L.) Moldenke*	T.suc	20	SI	257
214	G2	Su la dai	*Phoebe macrocarpa C.Y.Wu*	P.mac	20	SI	7
215	G2	Su la to	*Phoebe tavovana (Meissn.) Hook F.*	P.tav	20	SI	121
216	G2	Sung	*Ficus racemosa*	F.rac	30	SI	549
217	G2	Tam lang	*Barringtonia macrosatchya*	B.mac	20	SI	261
218	G2	Thanh nganh	*Cratoxylum formosum subsp.*	C.for	30	SI	868

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
			pruniflorum				
219	G2	Thanh that	*Ailanthus triphysa (Dennst.) Alston*	A.tri	25	SI	127
220	G2	Thau linh	*Alphonsea monogyna*	A.mon	25.4	SI	243
221	G2	Thau tau	*Aporusa villosa (Lind.) H. Baill.*	A.vil	25	SI	462
222	G2	Thoi ba	*Alangium chinense (Lour.) Harms*	A.chi	25	SI	189
223	G2	Thong nang	*Podocarpus imbricatus*	P.imb	30	SI	62
224	G2	Trac	*Dalbergia cochinchinensis*	D.coc	30	SI	14
225	G2	Trai ly	*Garcinia fagraeoides A.Chev.*	G.fag	25	SI	153
226	G2	Tram ba canh	*Canarium bengalense Roxb.*	C.ben	20	SI	153
227	G2	Tram den	*Canarium tramdennum*	C.tra	30	SI	2098
228	G2	Tram hoa xanh	*Syzygium chloranthum (Duthie)*	S.chl	24	SI	46
229	G2	Tram la do	*Canarium subulatum Guillaum*	C.sub	30	SI	12
230	G2	Tram mao	*Garuga pinnata Roxb*	G.pin	30	SI	4
231	G2	Tram trang	*Canarium album (Lour.) DC.*	C.alb	30	SI	29
232	G2	Truc tiet	*Carallia brachiata (Lour.) Merr.*	C.bra	25	SI	85
233	G2	Truong doi	*Arytera litoralis Blume*	A.lit	20	SI	6
234	G2	Truong hoi	*Tapiscia sinensis Oliv*	T.sin	22	SI	15
235	G2	Truong nuoc	*Paranephelium spirei*	P.spi	25	SI	344
236	G2	Truong quanh	*Xerospermum noronhiana*	X.nor	20	SI	233
237	G2	Truong sang	*Amesiodendron chinense*	A.chi	20	SI	261
238	G2	Uoi	*Scaphium macropodum (Miq.)*	S.mac	25	SI	315
239	G2	Uoi bay	*Scaphium lychnophorum Kost*	S.lyc	30	SI	120
240	G2	Vai rung	*Nephelium bassacense PIERRE*	N.bas	25	SI	53
241	G2	Vang anh	*Saraca dives Pierre*	S.div	28	SI	641
242	G2	Vang kieng	*Neonauclea purpurea (Roxb.) Merr.*	N.pur	20	SI	12
243	G2	Vang nghe	*Garcinia hanburyi Hook.f.*	G.han	20	SI	155
244	G2	Vap	*Mesua ferrea*	M.fer	30	SI	81
245	G2	Viet	*Madhuca cochinchinensis*	M.coc	25	SI	173

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
246	G2	Voi thuoc	*Schima wallichii Choisy*	S.wal	25	SI	522
247	G2	Xoai canh	*Swintonia floribunda*	S.flo	30	SI	27
248	G2	Xoai rung	*Mangifera minutifolia Evrand*	M.min	25	SI	354
249	G2	Xoan	*Melia azedarach L.*	M.aze	25	SI	16
250	G2	Xoan dao	*Prunus arborea (Blume) Kalkman*	P.arb	20	SI	517
251	G2	Xoan hoi	*Toona sinensis (Juss.) M.Roem.*	T.sin	30	SI	7
252	G2	Xoan nhu	*Choerospondias axillaris (Roxb.)*	C.axi	20	SI	267
253	G2	Xuong tran	*Platea latifolia*	P.lat	30	SI	82
254	G3	Bang lang	*Lagerstroemia calyculata*	L.cal	35	SI	1251
255	G3	Cho chi	*Parashorea chinensis Hsie Wang*	P.chi	50	SI	1134
256	G3	Cho nau	*Dipterocarpus retusus Blume*	D.ret	40	SI	266
257	G3	Cho nuoc	*Platanus kerrii*	P.ker	35	SI	43
258	G3	Cho xanh	*Terminalia myriocarpa*	T.myr	40	SI	54
259	G3	Cho xot	*Schima superba*	S.sup	40	SI	377
260	G3	Choai	*Terminalia bellirica*	T.bel	35	SI	58
261	G3	Chom chom rung	*Nephelium cuspidatum Blume*	N.cus	40	SI	34
262	G3	Dau rai	*Dipterocarpus alatus*	D.ala	50	SI	287
263	G3	De cau	*Quercus platycalyx Hickel & A.Camus*	Q.pla	42	SI	1279
264	G3	Den long	*Vitex canescens*	V.can	40	SI	220
265	G3	Gac da long	*Aphanamixis polystachya (Wall.)*	A.pol	32	SI	943
266	G3	Gioi la lang	*Michelia foveolata Merr. Ex Dandy*	M.fov	35	SI	84
267	G3	Gioi nhung	*Paramichelia braianensis*	P.bra	40	SI	47
268	G3	Go do	*Afzelia xylocarpa*	A.xyl	40	SI	14
269	G3	Goi gac	*Aphanamixis grandiflora Blume*	A.gra	40	SI	96
270	G3	Gu mat	*Sindora siamensis*	S.sia	35	SI	44
271	G3	Hoa khe	*Craibiodendron scleranthum*	C.scl	35	SI	41
272	G3	Hong quang	*Rhodoleia championii Hook*	R.cha	40	SI	66
273	G3	Huynh duong	*Dysoxylum loureiri*	D.lou	35	SI	254

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
274	G3	Khao vang	*Machilus bonii Lecomte*	M.bon	36	SI	702
275	G3	Long mang	*Sassafras tzumu*	S.tzu	35	SI	982
276	G3	Long mang la nho	*Pterospermum grewiaefolium*	P.gre	35	SI	91
277	G3	Mit nai	*Artocarpus rigidus ssp*	A.rig	45	SI	275
278	G3	Nhoi tia	*Bischofia javanica Blume*	B.jav	40	SI	241
279	G3	Phay	*Duabanga grandiflora (DC.) Walp.*	D.gra	35	SI	64
280	G3	Po mu	*Fokienia hodginsii*	F.hod	35	SI	106
281	G3	Re thom	*Machilus odoratissima*	M.odo	35	SI	26
282	G3	Re vang	*Machilus odoratissimus Nees*	M.odo	35	SI	505
283	G3	Sang da	*Hopea ferrea*	H.fer	35	SI	53
284	G3	Sang ma	*Carallia lucida*	C.luc	50	SI	33
285	G3	Sao den	*Hopea odorata Roxb*	H.odo	40	SI	72
286	G3	Sau sau	*Liquidambar formosana Hance*	L.for	40	SI	44
287	G3	Sen mat	*Madhuca pasquieri*	M.pas	40	SI	271
288	G3	Son xa	*Donella lanceolata (Blume) Aubr.*	D.lan	35	SI	26
289	G3	Sui	*Antiaris toxicaria*	A.tox	45	SI	41
290	G3	Tau la nho	*Vatica odorata ssp.brevipetiolata*	V.odo	35	SI	169
291	G3	Tau mat	*Vatica tonkinensis*	V.ton	35	SI	1003
292	G3	Tau muoi	*Vatica diospyroides*	V.dio	36	SI	370
293	G3	Thung	*Tetrameles nudiflora R. Br.*	T.nud	50	SI	206
294	G3	Thung muc	*Wrightia annamensis Eberh. & Dubard*	V.ann	35	SI	695
295	G3	Trai	*Shorea thorelii*	S.tho	40	SI	11
296	G3	Vang trung	*Endospermum chinense Benth.*	E.chi	35	SI	565
297	G3	Vay oc	*Diospyros buxifolia*	D.bux	35	SI	11
298	G3	Ven ven	*Anisoptera costata*	A.cos	40	SI	123
299	G3	Xoay rung	*Dialium cochinchinense Pierre*	D.coc	33	SI	198
300	G4	Bua	*Garcinia oblongifolia Champ. ex Benth*	G.obl	20	ST	1111

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
301	G4	Dung la nho	*Symplocos dolichotricha Merr*	S.dol	22	ST	291
302	G4	Dung la to	*Symplocos macrophylla sspsucata*	S.mac	22	ST	57
303	G4	Dung lua	*Symplocos sumuntia*	S.sum	23.4	ST	578
304	G4	Dung trang	*Symplocos groffii Merr*	S.gro	19.4	ST	61
305	G4	Ha nu	*Ixonanthes chinensis*	I.chi	20	ST	147
306	G4	Man rung	*Rhamnus crenata*	R.cre	21	ST	64
307	G4	Mau cho la to	*Knema pierrei Warb.*	K.pie	20	ST	1445
308	G4	Nang trung	*Hydnocarpus kurzii (King) Warb.*	H.kur	20	ST	439
309	G4	Ngoc lan	*Michelia alba*	M.alb	20	ST	16
310	G4	Nho vang	*Streblus macrophyllus Blume*	S.mac	22.6	ST	386
311	G4	Nu	*Garcinia tinctoria (DC.) W.Wight*	G.tin	20	ST	2
312	G4	Sen dat bon	*Sinosideroxylon bonii*	S.bon	22.5	ST	48
313	G4	Thi den	*Diospyros nitida Merr*	D.nit	20	ST	117
314	G4	Tram voi	*Syzygium cumini (L.) Skeels*	S.cum	20	ST	453
315	G5	Chap tay	*Symingtonia populnea (Griff.) Van Steenis*	S.pop	30	ST	69
316	G5	Chuon	*Calophyllum membranaceum*	C.mem	26	ST	165
317	G5	Mai tap	*Aidia oxyodonta (Drake) Yamaz*	A.oxy	25	ST	488
318	G5	Mau cho la nho	*Knema globularia (Lam.) Warb.*	K.glo	30	ST	690
319	G5	Thong tre	*Podocarpus neriifolius D.Don*	P.ner	25	ST	33
320	G6	Chan	*Microdesmis caseariifolia*	M.cas	12	ST	333
321	G6	Chan chim	*Schefflera heptaphylla (L.) Frodin*	S.hep	15	ST	1288
322	G6	Dau dat	*Baccaurea harmandii*	B.har	15	ST	9
323	G6	De bop	*Quercus poilanei*	Q.poi	16	ST	17
324	G6	Du du rung	*Trevesia palmata*	T.pal	9	ST	13
325	G6	Gach	*Trema tomentosa (Roxb.) Hara*	T.tom	11	ST	3
326	G6	Gang rung	*Randia spinosa (Thunb.) Poir*	R.spi	10	ST	11
327	G6	Gioi long	*Michelia balansae (A.DC.) Dandy*	M.bal	15	ST	49

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
328	G6	Go dong Bac	*Gordonia tonkinensis*	G.ton	12	ST	122
329	G6	Khong	*Koilodepas longifolium*	K.lon	13	ST	102
330	G6	Na hong	*Miliusa balansae Finet Et Gagnep*	M.bal	15	ST	54
331	G6	O ro	*Streblus ilicifolius (Vidal) Corner*	S.ili	10	ST	46
332	G6	Ruoi rung	*Streblus indicus*	S.ind	15	ST	73
333	G6	Sen gai	*Zanthoxylum acanthopodiun*	Z.aca	16	ST	45
334	G6	Sung rung	*Ficus septica Burm f var fistulosa*	F.sep	15	ST	67
335	G6	Tram do	*Syzygium jambos*	S.jam	12	ST	242
336	G6	Truong mat	*Pometia pinnata J, R, et G.Forst.*	P.pin	15	ST	526
337	G6	Xuong ca	*Canthium dicoccum (Gaertn.) Teysm*	C.dic	15	ST	127
338	G7	Bo	*Persea americana*	P.ame	20	IST	4
339	G7	Bong bac	*Vernonia arborea*	V.arb	20	IST	294
340	G7	Soi da	*Lithocarpus balansae (Drake) A. Camus*	L.bal	20	IST	27
341	G7	Song de	*Cleistanthus sumatranus*	C.sum	18	IST	62
342	G7	Thich la quat	*Acer flabellatum*	A.fla	15	IST	14
343	G7	Tong qua su	*Alnus nepalensis D.Don*	A.nep	20	IST	4
344	G7	Tram chim	*Bursera tonkinensis Guill*	B.ton	18	IST	71
345	G7	Tram vo do	*Syzygium zeylanicum (L.) DC*	S.zey	20	IST	2287
346	G8	Boi loi vong	*Litsea verticillata Hance*	L.ver	27	IST	215
347	G8	Long mang la hep	*Pterospermum angustifolium*	P.ang	30	IST	4
348	G8	Nhan rung	*Dimocarpus fumatus (Blume)*	D.fum	27	IST	242
349	G8	Re xanh	*Cinnadenia paniculata (Hook. f.) Kosterm*	C.pan	30	IST	21
350	G8	Soi de	*Lithocarpus harmandii*	L.har	25	IST	62
351	G8	Vang tam	*Manglietia fordiana (HEMSL.) OLIV.*	M.for	30	IST	221
352	G8	Voi	*Cleistocalyx nervosum (DC.) PhamHoang*	C.ner	25	IST	17

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
353	G8	Vu	*Endiandra hainanensis*	E.hai	25	IST	9
354	G8	Xoai gia	*Buchanania arborescens (BL) Bl.*	B.arb	25	IST	91
355	G9	Bo ket	*Gleditsia australis F.B.Forbes & Hemsl.*	G.aus	30	UI	6
356	G9	Bop la to	*Actinodaphne sesquipedalis*	A.ses	18	UI	5
357	G9	Cang cua	*Gymnosporia marcanii*	G.mar	4	UI	3
358	G9	Chua khet	*Glenniea philippinensis (Radlk.) Leenh*	G.phil	18	UI	128
359	G9	Cuong vang	*Gonocaryum lobbianum (Miers) Kurz*	G.lob	15	UI	296
360	G9	Cut mot	*Zollingeria dongnaiensis*	Z.don	30	UI	6
361	G9	Da long	*Ficus drupacea*	F.dru	15	UI	2
362	G9	Dang	*Schefflera tonkinensis*	S.ton	NA	UI	56
363	G9	Den nam la	*Vitex quinata (Lour.) Williams*	V.qui	25	UI	4
364	G9	Do quyen	*Rhododendron diaprepes*	R.dia	15	UI	21
365	G9	Dom dom	*Alchornea tiliaefolia*	A.til	12	UI	3
366	G9	Dung doi	*Symplocos racemosa Roxb*	S.rac	8	UI	8
367	G9	Gang	*Manilkara hexandra*	M.hex	15.6	UI	36
368	G9	Giang huong	*Pterocarpus macrocarpus Kurz*	P.mac	15	UI	7
369	G9	Hong dao	*Syzygium malaccense*	S.mal	10	UI	4
370	G9	Hu day long	*Celtis tomentosa Roxb*	C.tom	10	UI	4
371	G9	Ken	*Suregada multiflora (Juss) h. Baill.*	S.mul	15	UI	2
372	G9	Kha thu giap	*Castanopsis armata*	C.arm	30	UI	3
373	G9	Kha thu Pierre	*Castanopsis pierrei Hance*	C.pie	NA	UI	39
374	G9	Khao luoi nai	*Phoebe kunstleri Gamble*	P.kun	6	UI	1275
375	G9	Khao nui	*Machilus oreophila Hance*	M.ore	26	UI	102
376	G9	Khe	*Averrhoa carambola L.*	A.car	12	UI	36
377	G9	Khe rung	*Rourea minor ssp.microphylla*	R.min	NA	UI	6
378	G9	Nhoc la dai	*Polyalthia juncuda*	P.jun	15	UI	8
379	G9	Nong	*Saurauia napaulensis DC*	S.nap	10	UI	576
380	G9	Re bac	*Cinnamomum mairei*	C.mai	25	UI	2

Order	Group	Local name	Scientific name	Abbre-viation	Max attainable height (m)	Shade tolerance	No of individuals (tree)
381	G9	Re do	*Cinnamomun tetragonum A Cheva*	C.tet	32	UI	57
382	G9	San ho	*Jatropha multijida*	J.mul	25	UI	145
383	G9	Sang ngang	*Garcinia gaudichaudii*	G.gau	10	UI	75
384	G9	Sang nhung	*Sterculia lanceolata Cavan*	S.lan	NA	UI	249
385	G9	Sang quyt	*Taxatrophis ilicifolia*	T.ili	NA	UI	138
386	G9	Sang trang	*Lophopetalum duperreanum*	L.dup	20	UI	61
387	G9	Soi bang	*Triadica rotundifolia (Hemsl.) Esser*	T.rot	12	UI	3
388	G9	Soi Da nang	*Lithocarpus scortechinii*	L.sco	15	UI	6
389	G9	Soi huong	*Lithocarpus sphaerocarpus*	L.sph	30	UI	6
390	G9	Su la hep	*Phoebe angustifolia Meisn. in DC*	P.ang	NA	UI	39
391	G9	Sung	*Semecarpus tonkinensis*	S.ton	NA	UI	8
392	G9	Thach dam	*NA*	Sp1	NA	UI	80
393	G9	Thanh tra	*Bouea oppositifolia*	B.opp	20	UI	6
394	G9	Tra hoa	*Camellia krempfii (Gangnep.) Sealy*	C.kre	8	UI	2
395	G9	Tra rung	*Camellia chrysantha*	C.chr	NA	UI	66
396	G9	Tram sung	*Syzygium chanlos*	S.cha	NA	UI	451
397	G9	Trom Nam bo	*Sterculia cochinchinensis*	S.coc	20	UI	16
398	G9	Tu vi	*Lagerstroemia indica*	L.ind	6	UI	18
399	G9	Vang chang	*NA*	Sp	NA	UI	103
400	G9	Vang danh	*Fagraea fragrans Roxb*	F.fra	NA	UI	6
401	G9	Xoai	*Mangifera indica L.*	M.ind	25	UI	4

Note: SI – Shade intolerance; ST – Shade tolerance; IST – Intermediate shade tolerance; UI - Unidentified

APPENDIX II. General parameters of the permanent sample plots.

Region	plot	2005						2010						Increment (2005 – 2010)					
		No. stems	No. species	No. familie	dbh (cm; ± SE)	G (m^2 ha^{-1})	AGB (ton/ha)	No. stems	No. specie	No. families	dbh (cm; ± SE)	G (m2/ha	AGB (ton/ha)	No. species	No. familie	No. stems	dbh (cm)	G	AGB change
NE	1_1	831	30	15	17.52 ± 9.97	26.51	145.87	932	30	15	18.49 ± 10.61	33.25	180.47	0	0	101	0.97	6.74	34.6
NE	1_2	746	35	17	21.45 ± 13.47	37.54	222.1	785	35	16	22.63 ± 14.66	44.76	266.47	0	-1[*]	39	1.18	7.22	44.37
NE	1_3	508	31	20	22.9 ± 13.44	28.1	174.32	542	34	21	25.69 ± 13.94	30.83	192.83	3	1	34	2.80	2.73	18.51
NCC	10_1	1265	86	43	15.65 ± 9.78	33.8	213.16	1288	87	42	16.52 ± 9.39	36.18	230.74	1	-1	23	0.78	2.38	17.58
NCC	10_2	1249	76	39	14.6 ± 11.21	33.19	220.09	1238	80	41	17.25 ± 10.72	36.67	251.38	4	2	-11[*]	2.65	3.48	31.29
NCC	10_3	1174	79	43	16.55 ± 10.06	34.56	215.94	1198	84	44	18.8 ± 9.2	38.14	249.02	5	1	24	2.25	3.58	33.08
SCC	11_1	590	44	28	17.76 ± 10.57	19.78	126.82	615	45	29	20.13 ± 11.57	25.91	173.94	2	1	25	2.37	6.13	47.12
SCC	11_2	725	54	34	16.42 ± 10.42	21.52	132.68	784	54	34	18.93 ± 10.83	26.87	170	0	0	59	2.51	5.35	37.32
SCC	11_3	908	51	28	16.2 ± 10.45	26.47	168.7	948	51	28	18.6 ± 9.93	32.81	211.63	0	0	40	2.4	6.34	42.93
SW	12_1	909	26	20	10.43 ± 4.93	9.49	54.93	1136	34	25	11.13 ± 5.11	14.54	86.55	8	5	127	0.7	5.05	31.62
SW	12_2	1059	24	17	11.21 ± 5.08	12.59	73.53	1317	30	22	11.49 ± 5.26	16.54	101.69	6	5	258	0.28	3.95	28.16
SW	12_3	1021	32	25	10.1 ± 4.38	9.72	58.89	1233	41	29	10.81 ± 4.63	15.5	96.47	9	4	212	0.71	5.78	37.58
NW	13_1	351	39	24	19.31 ± 10.55	13.34	73.72	412	42	27	18.8 ± 11.07	15.38	87.74	3	3	61	-0.51[**]	2.04	14.02
NW	13_2	291	58	28	19.53 ± 12.29	12.15	77.2	363	67	32	18.93 ± 11.94	14.34	90.86	9	4	72	-0.6	2.19	13.66
NW	13_3	432	64	28	17.17 ± 8.92	12.69	79.13	542	70	31	17.3 ± 9.07	16.2	100.3	6	3	110	0.13	3.51	21.17
NW	14_1	498	52	30	14.74 ± 5.75	9.79	58.09	589	67	33	15.8 ± 6.94	11.44	68.96	15	3	91	1.06	1.65	10.87
NW	14_2	554	61	29	14.05 ± 5.83	10.07	60.61	583	74	33	15.19 ± 6.82	12.68	77.91	13	4	29	1.14	2.61	17.3
NW	14_3	420	44	29	15.88 ± 4.51	8.98	46.05	447	49	31	18.35 ± 6.16	13.01	70.09	5	2	27	2.47	4.03	24.04
NW	15_1	349	56	33	15.75 ± 7.74	8.43	46.34	439	54	32	20.59 ± 8.66	11.67	66.87	-2[*]	-1	90	4.84	3.24	20.53
NW	15_2	563	54	30	14.44 ± 8.03	12.06	65.6	601	51	30	18.38 ± 8.6	15.02	83	-3	0	38	3.94	2.96	17.4
NW	15_3	538	65	37	15.84 ± 9.2	14.16	84.42	600	75	37	16.93 ± 9.36	17.72	98.22	10	0	62	1.09	3.56	13.8
RRD	16_1	416	53	30	22.48 ± 17.69	26.69	184.88	425	52	30	26.83 ± 19.27	31.33	224.56	-1	0	9	4.35	4.64	39.68
RRD	16_2	634	61	29	19.89 ± 13.01	28.09	182.68	641	61	30	22.91 ± 13.24	33.62	214.51	0	1	7	3.02	5.53	31.83
RRD	16_3	858	78	39	16.76 ± 9.83	25.42	153.92	962	90	42	17.59 ± 9.89	30.63	196.63	12	3	104	0.83	5.21	42.71
NW	17_1	378	27	23	28.6 ± 21.91	38.48	321.07	421	32	24	27.6 ± 22.47	41.83	356.91	5	1	43	-1	3.35	35.84
NW	17_2	419	30	23	35.69 ± 28.57	68.69	651.68	425	36	25	36.51 ± 29.63	73.68	719.1	6	2	6	0.82	4.99	67.42
NW	17_3	358	32	25	31.36 ± 24.21	44.06	383.82	417	39	27	29.08 ± 25.13	48.31	439.4	7	2	59	-2.28	4.25	55.58
NE	18_1	180	27	20	12.41 ± 4.8	2.5	12.92	231	39	25	14.82 ± 5.83	4.63	27.79	12	5	51	2.41	2.13	14.87

NE	18_2	237	25	21	12.67 ± 5.57	3.56	18.81	465	49	30	12.43 ± 6.16	8.57	47.85	24	9	118	-0.24	5.01	29.04
NE	18_3	332	35	24	13.04 ± 6.27	5.46	27.43	402	44	27	13.09 ± 5.78	6.44	34.96	9	3	70	0.05	0.98	7.53
NW	19_1	753	72	34	12.96 ± 5.88	11.97	55.37	761	73	35	16.41 ± 6.05	17.75	90.98	1	1	8	3.45	5.78	35.61
NW	19_2	718	101	46	12.88 ± 6.11	11.45	55.6	723	103	46	16.19 ± 6.52	16.9	90.18	2	0	5	3.31	5.45	34.58
NW	19_3	459	70	35	16.14 ± 7.33	11.32	51.96	526	75	35	17.42 ± 7.72	15	72.93	5	0	67	1.28	3.68	20.97
SW	2_1	193	7	5	14.52 ± 8.77	4.35	23.02	214	7	5	17.38 ± 10.32	6.86	40.6	0	0	21	2.86	2.51	17.58
SW	2_2	224	6	5	20.55 ± 8.26	8.62	51.6	275	6	5	23.87 ± 9.38	10.78	72.47	0	0	51	3.32	2.16	20.87
SW	2_3	183	3	3	18.14 ± 8.53	5.77	31.3	187	3	3	20.35 ± 8.56	7.15	44.17	0	0	4	2.21	1.38	12.87
NCC	20_1	347	67	35	22.63 ± 16.8	21.61	169.57	371	70	35	22.79 ± 17.13	23.63	193.77	3	0	24	0.16	2.02	24.2
NCC	20_2	339	69	30	25.13 ± 17.74	25.15	201.58	385	74	31	24.93 ± 18.75	29.37	240.94	5	1	46	-0.2	4.22	39.36
NCC	20_3	330	62	33	23.41 ± 15.92	20.73	153.89	348	62	33	23.97 ± 16.32	22.96	177.74	0	0	18	0.56	2.23	23.85
NW	21_2	627	67	36	21.42 ± 10.35	27.84	163.1	681	75	38	20.97 ± 11.95	31.1	190.13	8	2	54	-0.45	3.26	27.03
NW	21_3	315	70	37	21.64 ± 11.89	15.07	86.37	369	85	43	20.75 ± 12.33	19.01	129.12	15	6	54	-0.89	6.94	42.75
NCC	22_1	278	46	26	15.73 ± 9.99	7.57	46.93	300	47	26	18.54 ± 9.83	10.36	63.68	1	0	22	2.81	2.79	16.75
NCC	22_2	368	57	27	17.67 ± 10.81	12.39	75.2	421	62	30	18.91 ± 10.89	15.73	96.77	5	3	53	1.24	3.34	21.57
NCC	22_3	392	62	33	16.77 ± 9.14	11.22	71.32	450	60	32	19.31 ± 9.77	12.86	81.07	-2	-1	58	2.54	1.64	9.75
RRD	23_1	387	27	14	24.36 ± 26.08	38.65	274.86	407	33	17	26.29 ± 27.78	43.54	301.2	6	3	20	1.93	4.89	26.34
RRD	23_2	709	45	26	21.69 ± 24.27	58.9	401.71	741	48	26	22.85 ± 24.06	63.19	430.11	3	0	32	1.16	4.29	28.4
RRD	23_3	712	52	25	20.23 ± 20.37	46.04	333.97	718	57	27	21.62 ± 20.63	49.79	353.9	5	2	6	1.39	3.75	19.93
NCC	24_1	582	51	25	18.13 ± 10.2	19.77	121.91	601	52	25	20.34 ± 10.65	20.73	131.18	1	0	19	2.21	0.96	9.27
NCC	24_2	574	69	39	18.6 ± 11.88	21.94	140.43	580	71	39	20.54 ± 11.6	24.19	167.78	2	0	6	1.94	2.25	27.35
NCC	24_3	528	56	31	19.66 ± 11.1	21.12	135.6	567	57	32	22.53 ± 12.32	24.15	161.69	1	1	39	2.87	3.03	26.09
NCC	25_1	709	70	32	22.41 ± 17.66	45.27	396.78	703	72	31	24.3 ± 17.56	47.44	418.77	2	-1	-6	1.89	2.17	21.99
NCC	25_2	833	83	39	23.07 ± 19.22	58.94	517.38	828	84	39	24.54 ± 19.48	59.91	536.83	1	0	-5	1.47	0.97	19.45
NCC	25_3	730	73	32	23.58 ± 20.56	56.05	492.98	726	75	32	25.09 ± 20.02	58.71	519.18	2	0	-4	1.51	2.66	26.2
NCC	261_1	466	66	32	18.49 ± 10.02	16.17	109.45	513	70	33	20.1 ± 11.34	21.44	151.21	4	1	47	1.61	5.27	41.76
NCC	261_2	487	66	31	18.26 ± 12.28	18.5	121.22	508	71	33	20.12 ± 12.17	22.02	148.46	5	2	21	1.86	3.52	27.24
NCC	27_1	414	53	32	20.63 ± 11.19	17.89	123.38	423	51	31	22.96 ± 11.88	21.13	145.82	-2	-1	9	2.33	3.24	22.44
NCC	27_2	392	59	30	20.73 ± 11.92	17.58	131.12	402	59	29	24.28 ± 12.71	21.92	164.99	0	-1	10	3.55	4.34	33.87
NCC	27_3	437	70	34	19.1 ± 12.46	17.82	110.84	484	65	32	21.45 ± 12.5	18.55	125.42	-5	-2	47	2.35	0.73	14.58
NCC	28_1	566	69	35	21.89 ± 15.31	31.68	228.77	591	70	35	23.08 ± 14.53	35.34	258.37	1	0	25	1.19	3.66	29.6
NCC	28_2	527	69	35	21.33 ± 15.23	28.4	192.52	535	73	36	22.02 ± 15.32	29.7	209	4	1	8	0.69	1.3	16.48
NCC	28_3	515	69	33	22.11 ± 14.92	28.73	211.27	539	73	34	22.97 ± 15.14	32.13	243.39	4	1	24	0.86	3.4	32.12

NCC	29_1	695	60	31	10.51 ± 3.7	6.77	25.8	771	75	36	13.41 ± 4.67	13.24	56.52	15	5	76	2.9	6.47	30.72
NCC	29_2	848	80	38	11.18 ± 3.88	9.31	36.2	854	86	40	13.46 ± 5.09	14.92	65.33	6	2	6	2.28	5.61	29.13
NCC	29_3	757	78	40	11.85 ± 4.99	9.82	42.39	775	83	39	14.56 ± 6.14	16.62	82.25	5	-1	18	2.71	6.8	39.86
RRD	3_1	364	32	20	24.34 ± 9.71	19.61	129.91	387	35	24	25 ± 11.1	22.66	157.22	3	4	23	0.66	3.05	27.31
RRD	3_2	375	30	23	26.81 ± 9.61	23.87	166.17	395	33	25	28 ± 11.04	28.08	204.89	3	2	20	1.19	4.21	38.72
RRD	3_3	350	41	27	26.79 ± 11.65	23.44	158.31	383	43	28	27.45 ± 13.3	27.93	196.86	2	1	33	0.66	4.49	38.55
NCC	30_1	1373	79	37	13.49 ± 5.89	23.36	129.04	1477	84	37	15.65 ± 6.26	32.25	190.05	5	0	104	2.16	8.89	61.01
NCC	30_2	1381	75	38	13.93 ± 8.16	28.25	153.9	1507	80	39	16.03 ± 7.62	36.41	205.97	5	1	126	2.1	8.16	52.07
NCC	30_3	896	94	43	17.18 ± 10.27	28.16	171.79	971	100	43	18.83 ± 9.84	33.87	213.12	6	0	75	1.65	5.71	41.33
SCC	31_1	732	65	33	12.45 ± 5.83	10.86	48.28	773	68	34	15.43 ± 6.55	17.07	79.56	3	1	41	2.98	6.21	31.28
SCC	31_2	943	57	38	14.6 ± 8.12	20.65	115.09	982	58	36	16.91 ± 8.45	24.82	143.8	1	-2	39	2.31	4.17	28.71
SCC	31_3	1268	69	38	14.1 ± 6.35	23.81	120.35	1422	79	39	15.55 ± 7.06	32.63	176.99	10	1	154	1.45	8.82	56.64
SCC	32_1	846	61	36	15.82 ± 9.3	22.35	133.91	868	67	39	17.75 ± 9.7	27.76	167.27	6	3	22	1.93	5.41	33.36
SCC	32_2	773	69	35	16.16 ± 9.58	21.42	131.26	798	73	38	18.44 ± 9.72	25.32	153.91	4	3	25	2.28	3.9	22.65
SCC	32_3	827	76	38	15.64 ± 9.52	21.77	133.18	876	80	38	18.59 ± 9.26	29.25	181.69	4	0	49	2.95	7.48	48.51
CH	33_1	612	48	30	23.08 ± 16.05	37.96	238.61	639	55	33	23.72 ± 15.95	40.87	264.19	7	3	27	0.64	2.91	25.58
CH	33_2	677	51	31	22.03 ± 17.37	41.8	276.33	760	54	34	22.24 ± 16.64	45.96	299.49	3	3	83	0.21	4.16	23.16
CH	33_3	822	57	31	21.53 ± 13.16	41.08	259.45	888	66	34	21.54 ± 13.25	44.55	292.13	9	3	66	0.01	3.47	32.68
CH	34_1	623	67	30	19.14 ± 15.62	29.83	199.01	625	66	30	20.85 ± 15.42	32.96	233.38	-1	0	2	1.71	3.13	34.37
CH	34_2	633	68	31	20.49 ± 18.7	38.21	293.65	654	67	31	22.83 ± 17.56	39.44	314.63	-1	0	21	2.34	1.23	20.98
CH	34_3	691	75	35	19.28 ± 16.34	34.63	268.48	704	74	35	21.73 ± 15.96	36.72	286.93	-1	0	13	2.45	2.09	18.45
CH	35_1	1059	77	38	16.85 ± 12.64	36.86	257.91	1076	76	37	19.66 ± 12.25	40.89	286.85	-1	-1	17	2.81	4.03	28.94
CH	35_2	929	66	36	17.61 ± 14.5	37.93	297.41	962	65	36	20.41 ± 14.08	41.54	332.31	-1	0	33	2.8	3.61	34.9
CH	35_3	884	75	40	17.51 ± 13.77	34.43	241.12	908	73	39	19.98 ± 13.73	37.21	267.31	-2	-1	24	2.47	2.78	26.19
SCC	36_1	1283	88	40	16.05 ± 9.3	34.64	235.25	1312	86	39	18.73 ± 8.79	41.02	275.11	-2	-1	29	2.68	6.38	39.86
SCC	36_2	1097	90	41	16.6 ± 12.14	36.42	260.92	1112	88	40	19.12 ± 11.56	41.99	290.96	-2	-1	15	2.52	5.57	30.04
SCC	36_3	931	93	39	18.12 ± 11.16	33.1	236.81	962	92	40	20.89 ± 11.07	37.8	269.08	-1	1	31	2.77	4.7	32.27
SE	37_1	601	34	24	17.37 ± 19.29	31.77	270.63	593	35	25	19.88 ± 18.3	33.96	290.9	1	1	-8	2.51	2.19	20.27
SE	37_2	702	30	23	18.6 ± 24.43	51.92	506.63	709	29	22	21.09 ± 24.39	52.93	522.75	-1	-1	7	2.49	1.01	16.12
SE	37_3	890	36	24	19.11 ± 21.32	57.21	528.31	910	38	25	22.1 ± 20.16	61.79	568.98	2	1	20	2.99	4.58	40.67
SE	39_1	543	43	34	17.1 ± 14.29	20.21	174.55	553	43	35	20.26 ± 15.51	25.7	216.61	0	1	10	3.16	5.78	42.06
SE	39_2	732	43	30	15.24 ± 10.5	19.67	157.59	757	43	31	17.66 ± 11.24	25.97	209.67	0	1	25	2.42	6.3	52.08
SE	39_3	695	50	31	15.86 ± 12.4	22.1	189.2	719	45	29	18.74 ± 13.57	26.53	227.31	-5	-2	24	2.88	4.43	38.11

NW	4_1	275	14	13	22.1 ± 9.98	12.68	86.69	311	16	13	22.44 ± 10.11	14.78	100.88	2	0	36	0.34	2.1	14.19
NW	4_2	253	10	9	22.56 ± 9.54	11.91	82.66	308	22	16	21.05 ± 10.86	15.76	113.24	12	7	55	-1.51	3.85	30.58
NW	4_3	298	10	9	22.92 ± 9.66	14.46	98.52	375	14	12	21.9 ± 10.95	17.65	124.41	4	3	77	-1.02	3.19	25.89
SW	40_1	729	53	34	15.5 ± 13.16	23.65	203.04	768	59	35	16.82 ± 13.51	26.47	225.6	6	1	39	1.32	2.82	22.56
SW	40_2	985	47	28	14.95 ± 10.55	25.87	223.5	1008	52	30	16.5 ± 10.8	29.29	243.03	5	2	23	1.55	3.42	19.53
SW	40_3	930	45	28	15.09 ± 11.5	26.27	212.73	986	49	30	16.98 ± 12.04	30.13	236.03	4	2	56	1.89	3.86	23.3
NE	41_1	552	56	31	14.95 ± 11.22	15.13	92.03	582	58	31	17.43 ± 11.53	16.51	103.96	2	0	30	2.48	1.38	11.93
NE	41_2	592	58	35	14.04 ± 9.51	13.36	74.57	608	66	33	16.23 ± 10.12	15.45	88.29	8	-2	16	2.19	2.09	13.72
NE	41_3	545	50	30	17.89 ± 14.08	22.17	141.56	553	48	29	20.02 ± 14.96	25.04	174.46	-2	-1	8	2.13	2.87	32.9
NW	42_1	492	38	20	20.2 ± 11.43	20.8	154.41	612	76	34	19.18 ± 11.15	24.27	180.39	38	14	120	-1.02	3.47	25.98
NW	42_3	566	34	20	19.86 ± 6.8	20.98	142.73	735	38	22	19.16 ± 10.03	26.98	188.99	4	2	169	-0.7	6	46.26
SE	43_1	864	63	33	12.85 ± 6.8	14.33	85.78	879	62	33	15.04 ± 7.89	19.21	123.28	-1	0	15	2.19	4.88	37.5
SE	43_2	735	58	30	13.84 ± 7.86	14.62	87.72	746	58	30	16.57 ± 8.92	20.73	133.82	0	0	11	2.73	6.11	46.1
SE	43_3	954	57	31	12.57 ± 7.13	15.63	93.95	963	56	31	15.19 ± 7.83	21.62	136.9	-1	0	9	2.62	5.99	42.95
NW	44_1	456	62	35	13.62 ± 6.31	8.06	40.66	596	71	37	14.07 ± 6.79	12.76	67.46	9	2	140	0.45	4.7	26.8
NW	44_2	413	68	34	17.33 ± 11.29	13.87	76.83	510	85	38	16.46 ± 10.34	18.09	105.59	17	4	97	-0.87	4.22	28.76
NW	44_3	376	65	35	16.58 ± 9.5	10.77	58.53	502	79	38	16.67 ± 9.45	14.64	81.71	14	3	126	0.09	3.87	23.18
NW	45_1	450	37	21	20.27 ± 12.36	19.91	159.47	563	39	21	19.81 ± 13.31	25.16	212.13	2	0	113	-0.46	5.25	52.66
NW	45_2	428	28	18	19.7 ± 10.59	16.79	131.38	537	31	19	18.69 ± 11.67	20.44	172.34	3	1	109	-1.01	3.65	40.96
NW	46_1	563	46	29	19.88 ± 18.04	31.82	209.42	575	58	34	22.1 ± 19.57	34.36	222.44	12	5	12	2.22	2.54	13.02
NW	46_2	532	46	26	12.96 ± 5.79	8.41	49.63	553	53	30	14.25 ± 6.87	10.86	62.42	7	4	21	1.29	2.45	12.79
NW	46_3	361	40	26	12.57 ± 5.23	5.25	28.01	453	59	35	13.09 ± 6.43	8.22	44.59	19	9	92	0.52	2.97	16.58
NCC	47_1	883	67	35	17.08 ± 12.55	31.13	212.87	912	69	35	19 ± 13.29	33.95	236.18	2	0	29	1.92	2.82	23.31
NCC	47_2	804	77	40	18.07 ± 12.9	31.11	209.02	832	85	40	19.31 ± 13.29	33.76	233.21	8	0	28	1.24	2.65	24.19
NCC	47_3	1096	73	39	16.08 ± 11.03	32.71	215.09	1134	75	39	17.26 ± 11.07	37.27	247.51	2	0	38	1.18	4.56	32.42
NCC	48_1	762	73	36	18.17 ± 13.16	30.09	184.19	858	85	40	18.06 ± 13.24	34.11	215.35	12	4	96	-0.11	4.02	31.16
NCC	48_2	974	75	37	17.52 ± 13.28	36.93	208.15	1011	88	39	18.32 ± 13.6	40.85	248.61	13	2	37	0.8	3.92	40.46
NCC	48_3	871	76	37	16.82 ± 11.93	29.05	165.48	901	80	38	18.04 ± 12.42	34.17	207.5	4	1	30	1.22	5.12	42.02
CH	49_1	572	61	34	21.7 ± 18.39	36.31	278.6	617	67	38	22.22 ± 18.04	39.73	311.51	6	4	45	0.52	3.42	32.91
CH	49_2	1078	56	34	15.39 ± 10.15	28.75	202.41	1137	65	38	16.57 ± 9.75	32.55	236.39	9	4	59	1.18	3.8	33.98
CH	49_3	416	73	38	21.5 ± 20.49	28.77	228.95	445	79	41	22.18 ± 20.01	31.09	255.07	6	3	29	0.68	2.32	26.12
RRD	5_1	927	30	21	15.39 ± 9.77	24.17	142.09	939	31	21	18.42 ± 10.01	30.51	184.51	1	0	12	3.03	6.34	42.42
RRD	5_2	641	37	25	16.18 ± 10.36	18.56	112.02	650	40	28	17.94 ± 10.17	21.54	131.7	3	3	9	1.76	2.98	19.68

RRD	5_3	675	33	23	17.24 ± 12.18	23.59	146.62	700	30	22	20.35 ± 12.62	28.31	187.91	-3	-1	25	3.11	4.72	41.29
CH	50_1	677	66	36	19.21 ± 13.87	29.82	240.35	706	72	37	20.73 ± 13.45	33.68	271.6	6	1	29	1.52	3.86	31.25
CH	50_2	713	59	31	20.33 ± 14.39	34.7	280.79	751	64	34	21.15 ± 13.88	37.69	312.21	5	3	38	0.82	2.99	31.42
CH	50_3	621	73	34	21.75 ± 15.65	34.98	249.98	627	74	35	23.86 ± 14.51	38.41	277.27	1	1	6	2.11	3.43	27.29
CH	51_1	759	77	40	18.65 ± 15.66	35.3	260.22	765	75	40	20.99 ± 15.09	37.5	288.38	-2	0	6	2.34	2.2	28.16
CH	51_2	764	87	42	18.65 ± 14.26	33.04	268.36	768	83	42	20.72 ± 14.11	34.92	291.72	-4	0	4	2.07	1.88	23.36
CH	51_3	639	77	40	20.39 ± 15.51	32.89	246.15	649	79	39	22.22 ± 15.22	35.45	280.34	2	-1	10	1.83	2.56	34.19
CH	52_1	562	72	41	18.93 ± 15.39	26.24	207.34	568	72	41	21.98 ± 15.66	29.59	236.62	0	0	6	3.05	3.35	29.28
CH	52_2	559	79	41	19.96 ± 16.89	29.97	247.3	565	74	41	22.24 ± 16.78	31.34	267.98	-5	0	6	2.28	1.37	20.68
CH	52_3	528	62	36	19.38 ± 16.56	26.91	221.61	536	61	37	21.65 ± 16.49	29.37	245.59	-1	1	8	2.27	2.46	23.98
NE	6_1	231	45	31	27.6 ± 27.11	27.08	185.14	225	46	32	30.17 ± 27.81	29.46	205.46	1	1	-6	2.57	2.38	20.32
NE	6_2	271	46	32	27.36 ± 33.72	40.02	297.01	282	53	34	27.11 ± 33.66	41.16	305.44	7	2	11	-0.25	1.14	8.43
NE	6_3	415	51	35	26.55 ± 32.9	58.15	388.9	409	50	34	28.22 ± 33.4	61.2	410.7	-1	-1	-6	1.67	3.05	21.8
NCC	7_1	217	21	13	43.14 ± 19.62	38.23	328.9	212	21	13	45.78 ± 19.27	40.6	357.52	0	0	-5	2.64	2.37	28.62
NCC	7_2	249	20	14	43.45 ± 21.54	45.93	390.65	255	21	14	44.71 ± 21.27	47.11	410.27	1	0	6	1.26	1.18	19.62
NCC	7_3	369	34	17	34.95 ± 21.78	49.08	419.14	373	33	16	39.87 ± 22.54	51.5	446.04	-1	-1	4	4.92	2.42	26.9
NCC	9_1	990	69	37	11.39 ± 6.68	13.54	70.57	980	79	40	13.25 ± 6.96	15.78	87.11	10	3	-10	1.86	2.24	16.54
NCC	9_2	1000	78	41	13.61 ± 6.99	18.37	96.61	1106	88	41	14.26 ± 7.1	21.77	118.78	10	0	106	0.65	3.4	22.17
NCC	9_3	984	85	43	13.97 ± 7.06	18.92	102.77	1095	92	43	14.65 ± 7.26	22.8	127.57	7	0	111	0.68	3.88	24.8
Mean±SE		**639 ± 272[a]**	**56 ± 20**	**30 ± 8**	**18.68 ± 0.43**	**24.80 ± 13.01[c]**	**174.97 ± 114.95[e]**	**663 ± 281[b]**	**60 ± 21**	**32±8**	**20.19 ± 0.42**	**28.59 + 12.95[d]**	**204.11 ± 117.38[f]**					**4.47 ± 2.03)**	**29.15 ± 11.81**

** Negative values indicate no increment of dbh in the period of 5 years.

[a, b] indicate significant difference of number of stems between 2005 and 2010 ($p < 0.01$).

[c, d] indicate significant difference of G between 2005 and 2010 ($p < 0.01$).

[a, b] indicate significant difference of AGB between 2005 and 2010 ($p < 0.01$).

Ecoregions: NW: Northwest; NC: North Central Coast; NE: Northeast; CH: Central Highlands; SE: Southeast: SW: Southwest; RR: Red River Delta; SC: South Central Coast

APPENDIX III. Recruited stems, dead stems and annual G and AGB increment.

Region	Plot	Dead trees				Recruited trees				Increment	
		No. stems	Mortality rate	AGB mortality (ton ha^{-1})	AGB mortality rate	No. stems	Recruitment rate	AGB* recruitment rate (ton ha^{-1})	AGB recruitment rate	G (m^2 ha^{-1})	AGB (ton ha^{-1} year^{-1})
NE	1_1	25	0.006	2.96	0.004	125	0.032	1.82	0.0020	1.348	6.92
NE	1_2	36	0.010	8.15	0.007	75	0.021	1.5	0.0011	1.444	8.874
NE	1_3	37	0.015	12.56	0.015	73	0.031	0.44	0.0005	0.546	3.702
NCC	10_1	14	0.002	55.4	0.058	35	0.006	5.08	0.0044	0.476	3.516
NCC	10_2	54	0.009	62.81	0.065	45	0.007	2.8	0.0022	0.696	6.258
NCC	10_3	40	0.007	61.51	0.065	66	0.012	2.99	0.0024	0.716	6.616
SCC	11_1	33	0.011	7.21	0.012	60	0.021	1.46	0.0016	1.226	9.424
SCC	11_2	66	0.019	18.59	0.030	125	0.037	1.54	0.0018	1.07	7.464
SCC	11_3	29	0.006	30.17	0.039	69	0.016	1.24	0.0012	1.268	8.586
SW	12_1	64	0.013	3.93	0.015	190	0.041	6.15	0.0146	1.01	6.324
SW	12_2	105	0.021	9.21	0.026	353	0.078	6.81	0.0138	0.79	5.632
SW	12_3	67	0.013	3.68	0.013	275	0.061	8.75	0.0188	1.156	7.516
NW	13_1	31	0.018	4.18	0.012	92	0.059	2.25	0.0052	0.408	2.804
NW	13_2	25	0.018	6.74	0.018	96	0.077	5.35	0.0121	0.438	2.732
NW	13_3	31	0.015	7.71	0.020	140	0.075	5.92	0.0120	0.702	4.234
NW	14_1	61	0.026	16.3	0.064	157	0.073	5.4	0.0162	0.33	2.174
NW	14_2	57	0.021	16.64	0.062	84	0.032	3.17	0.0083	0.522	3.46
NW	14_3	59	0.030	4.89	0.022	83	0.043	2.84	0.0082	0.806	4.808
NW	15_1	32	0.019	4.28	0.019	120	0.081	4.9	0.0151	0.648	4.106
NW	15_2	116	0.045	10.29	0.034	152	0.061	2.13	0.0052	0.592	3.48
NW	15_3	106	0.043	16.3	0.042	163	0.070	4.7	0.0098	0.712	2.76
RRD	16_1	51	0.026	4.83	0.005	61	0.031	2.36	0.0021	0.928	7.936
RRD	16_2	25	0.008	11.73	0.013	33	0.011	1.25	0.0012	1.106	6.366
RRD	16_3	97	0.024	20.74	0.029	204	0.053	3.83	0.0039	1.042	8.542
NW	17_1	17	0.009	2.8	0.002	60	0.034	1.35	0.0008	0.67	7.168
NW	17_2	27	0.013	14.98	0.005	33	0.016	0.58	0.0002	0.998	13.484
NW	17_3	21	0.012	2.87	0.001	79	0.049	1.64	0.0007	0.85	11.116
NE	18_1	9	0.010	0.56	0.009	58	0.075	2.43	0.0181	0.426	2.974
NE	18_2	15	0.009	2.4	0.027	120	0.081	3.92	0.0169	1.002	5.808
NE	18_3	41	0.026	5.4	0.043	112	0.079	2.73	0.0161	0.196	1.506

NW	19_1	26	0.007	5.82	0.022	34	0.009	2.1	0.0047	1.156	7.122
NW	19_2	19	0.005	2.41	0.009	25	0.007	0.95	0.0021	1.09	6.916
NW	19_3	68	0.032	11.88	0.051	134	0.067	4.78	0.0135	0.736	4.194
SE	2_1	8	0.008	0.81	0.007	27	0.030	0.43	0.0021	0.502	3.516
SE	2_2	27	0.025	5.14	0.021	79	0.083	2.16	0.0060	0.432	4.174
SE	2_3	4	0.004	1.31	0.009	9	0.010	0.08	0.0004	0.276	2.574
NCC	20_1	33	0.020	31.86	0.041	57	0.035	0.82	0.0008	0.404	4.84
NCC	20_2	12	0.007	25.34	0.027	57	0.036	1.05	0.0009	0.844	7.872
NCC	20_3	21	0.013	25.95	0.036	27	0.017	0.65	0.0007	0.446	4.77
NW	21_2	109	0.037	27.17	0.036	166	0.060	8.84	0.0117	0.652	5.406
NW	21_3	23	0.015	12	0.029	78	0.055	6.53	0.0103	0.788	8.55
NCC	22_1	2	0.001	0.1	0.000	25	0.019	1.23	0.0039	0.558	3.35
NCC	22_2	8	0.004	1.29	0.003	61	0.036	3.9	0.0082	0.668	4.314
NCC	22_3	56	0.030	13.66	0.042	113	0.066	4.7	0.0119	0.328	1.95
RRD	23_1	41	0.022	4.62	0.003	61	0.034	0.85	0.0006	0.978	5.268
RRD	23_2	61	0.018	43.33	0.023	91	0.027	2.5	0.0012	0.858	5.68
RRD	23_3	26	0.007	23.61	0.015	32	0.009	2.19	0.0012	0.75	3.986
NCC	24_1	105	0.039	23.06	0.041	124	0.047	0.47	0.0007	0.192	1.854
NCC	24_2	95	0.036	24.88	0.038	102	0.038	3.52	0.0042	0.45	5.47
NCC	24_3	88	0.036	12.98	0.020	125	0.053	3.92	0.0049	0.606	5.218
NCC	25_1	52	0.015	72.29	0.039	45	0.013	2.65	0.0013	0.434	4.398
NCC	25_2	76	0.019	114.86	0.049	72	0.018	1.69	0.0006	0.194	3.89
NCC	25_3	18	0.005	73.6	0.032	15	0.004	1.27	0.0005	0.532	5.24
NCC	261_1	18	0.008	5.6	0.010	64	0.029	2.1	0.0028	1.054	8.352
NCC	261_2	24	0.010	13.22	0.023	45	0.019	1.69	0.0023	0.704	5.448
NCC	27_1	21	0.010	7.59	0.013	30	0.015	1.7	0.0023	0.648	4.488
NCC	27_2	31	0.016	1.21	0.002	41	0.022	1.8	0.0022	0.868	6.774
NCC	27_3	61	0.030	21.9	0.043	105	0.053	3.52	0.0057	0.146	2.916
NCC	28_1	43	0.016	52.03	0.050	61	0.023	6.27	0.0073	0.732	5.92
NCC	28_2	76	0.031	34.67	0.039	84	0.034	3.12	0.0030	0.26	3.296
NCC	28_3	50	0.020	22.54	0.022	74	0.031	4.75	0.0039	0.68	6.424
NCC	29_1	113	0.035	4.02	0.033	189	0.062	4.6	0.0168	1.294	6.144
NCC	29_2	97	0.024	7.87	0.048	102	0.025	5.6	0.0178	1.122	5.826
NCC	29_3	121	0.034	7.03	0.036	138	0.039	7.4	0.0187	1.36	7.972
RRD	3_1	9	0.005	2.18	0.003	31	0.018	0.68	0.0009	0.61	5.462
RRD	3_2	2	0.001	0.16	0.000	21	0.011	0.42	0.0004	0.842	7.744
RRD	3_3	2	0.001	1.2	0.002	35	0.021	0.64	0.0007	0.898	7.71

NCC	30_1	54	0.008	13.11	0.021	160	0.024	6.5	0.0069	1.778	12.202
NCC	30_2	49	0.007	27.8	0.039	177	0.027	6.19	0.0061	1.632	10.414
NCC	30_3	53	0.012	31.44	0.040	126	0.030	5.37	0.0051	1.142	8.266
SCC	31_1	52	0.015	6.8	0.030	92	0.027	3.08	0.0079	1.242	6.256
SCC	31_2	60	0.013	12	0.022	98	0.022	3.39	0.0048	0.834	5.742
SCC	31_3	9	0.001	5.19	0.009	164	0.027	7.31	0.0084	1.764	11.328
SCC	32_1	85	0.021	28.58	0.047	108	0.027	0.74	0.0009	1.082	6.672
SCC	32_2	117	0.032	37.37	0.065	143	0.040	0.81	0.0011	0.78	4.53
SCC	32_3	32	0.008	18.45	0.029	82	0.021	2.09	0.0023	1.496	9.702
CH	33_1	66	0.023	31.21	0.028	90	0.031	2.22	0.0017	0.582	5.116
CH	33_2	50	0.015	45.32	0.035	103	0.032	2.46	0.0016	0.832	4.632
CH	33_3	98	0.025	44.22	0.037	150	0.039	4.44	0.0031	0.694	6.536
CH	34_1	32	0.010	31.08	0.033	35	0.011	1.1	0.0009	0.626	6.874
CH	34_2	32	0.010	54.62	0.040	54	0.018	1.72	0.0011	0.246	4.196
CH	34_3	2	0.001	25.07	0.019	16	0.005	0.98	0.0007	0.418	3.69
CH	35_1	94	0.018	49.94	0.042	111	0.022	2.14	0.0015	0.806	5.788
CH	35_2	70	0.016	52.17	0.038	105	0.024	2.78	0.0017	0.722	6.98
CH	35_3	102	0.024	54.6	0.050	124	0.030	1.27	0.0010	0.556	5.238
SCC	36_1	96	0.015	50.35	0.047	125	0.020	1.89	0.0014	1.276	7.972
SCC	36_2	57	0.011	48.13	0.040	81	0.015	2.56	0.0018	1.114	6.008
SCC	36_3	77	0.017	46.48	0.043	109	0.025	1.42	0.0011	0.94	6.454
SE	37_1	22	0.007	53.2	0.043	15	0.005	0.51	0.0004	0.438	4.054
SE	37_2	80	0.024	88.3	0.038	87	0.026	3.51	0.0013	0.202	3.224
SE	37_3	22	0.005	82.39	0.033	41	0.009	2.22	0.0008	0.916	8.134
SE	39_1	22	0.008	2.83	0.003	25	0.009	1.34	0.0011	1.098	8.412
SE	39_2	34	0.009	2.89	0.004	47	0.013	2.45	0.0023	1.26	10.416
SE	39_3	88	0.027	22.26	0.025	113	0.035	3.12	0.0028	0.886	7.622
NW	4_1	12	0.009	10.87	0.026	49	0.038	3.79	0.0076	0.42	2.838
NW	4_2	22	0.018	7.99	0.020	78	0.071	3.78	0.0068	0.77	6.116
NW	4_3	25	0.017	6.86	0.014	100	0.079	3.8	0.0062	0.638	5.178
SW	40_1	96	0.028	43.2	0.047	136	0.040	3.01	0.0027	0.564	4.512
SW	40_2	116	0.025	28.79	0.027	143	0.031	2.01	0.0017	0.684	3.906
SW	40_3	78	0.017	17.73	0.017	131	0.030	1.39	0.0012	0.772	4.66
NE	41_1	91	0.035	17.44	0.041	122	0.049	0.43	0.0008	0.276	2.386
NE	41_2	98	0.036	13.67	0.040	114	0.042	1.02	0.0023	0.418	2.744
NE	41_3	88	0.035	21.33	0.032	94	0.037	2.49	0.0029	0.574	6.58
NW	42_1	65	0.028	27	0.038	184	0.089	4.34	0.0164	0.694	5.196

NW	42_3	36	0.013	10.72	0.015	199	0.083	4.47	0.0048	1.2	9.252
SE	43_1	1	0.000	0.05	0.000	17	0.004	0.96	0.0016	0.976	7.5
SE	43_2	2	0.001	0.96	0.002	13	0.004	1.2	0.0018	1.222	9.22
SE	43_3	47	0.010	8.33	0.018	57	0.012	2.3	0.0034	1.198	8.59
NW	44_1	22	0.010	2.76	0.014	165	0.086	5.63	0.0173	0.94	5.36
NW	44_2	38	0.019	13.4	0.038	135	0.076	8.06	0.0158	0.844	5.752
NW	44_3	17	0.009	12.52	0.047	138	0.087	4.73	0.0118	0.774	4.636
NW	45_1	4	0.002	0.45	0.001	119	0.060	2.46	0.0023	1.05	10.532
NW	45_2	16	0.008	7.24	0.011	125	0.067	2.18	0.0025	0.73	8.192
NW	46_1	88	0.033	60.36	0.066	101	0.039	4.44	0.0040	0.508	2.604
NW	46_2	70	0.028	8.13	0.035	89	0.036	3.9	0.0128	0.49	2.558
NW	46_3	33	0.019	6.5	0.051	127	0.083	3.94	0.0183	0.594	3.316
NCC	47_1	130	0.031	44.54	0.046	159	0.039	2.16	0.0018	0.564	4.662
NCC	47_2	133	0.036	41.87	0.044	162	0.044	5.42	0.0047	0.53	4.838
NCC	47_3	167	0.033	52.85	0.055	205	0.041	4.66	0.0038	0.912	6.484
NCC	48_1	97	0.027	43.18	0.052	192	0.056	4.6	0.0043	0.804	6.232
NCC	48_2	156	0.034	50.75	0.054	193	0.043	3.81	0.0031	0.784	8.092
NCC	48_3	150	0.037	37.64	0.050	181	0.046	4.03	0.0039	1.024	8.404
CH	49_1	56	0.020	49.17	0.038	104	0.039	5.13	0.0033	0.684	6.582
CH	49_2	74	0.014	35.43	0.038	132	0.026	2.01	0.0017	0.76	6.796
CH	49_3	35	0.017	29.8	0.028	73	0.038	2.05	0.0016	0.464	5.224
RRD	5_1	42	0.009	2.3	0.003	55	0.012	1.69	0.0018	1.268	8.484
RRD	5_2	66	0.021	15.66	0.030	101	0.034	2.51	0.0038	0.596	3.936
RRD	5_3	74	0.023	7.72	0.011	99	0.031	2.34	0.0025	0.944	8.258
CH	50_1	53	0.016	47.81	0.043	82	0.025	1.74	0.0013	0.772	6.25
CH	50_2	45	0.013	20.07	0.015	84	0.025	2.39	0.0015	0.598	6.284
CH	50_3	62	0.021	62.34	0.056	65	0.022	4.04	0.0029	0.686	5.458
CH	51_1	50	0.014	48.08	0.040	56	0.015	1.85	0.0013	0.44	5.632
CH	51_2	76	0.021	56.8	0.046	81	0.022	3.2	0.0022	0.376	4.672
CH	51_3	46	0.015	37.66	0.033	57	0.019	2.1	0.0015	0.512	6.838
CH	52_1	54	0.020	38.48	0.040	59	0.022	2.45	0.0021	0.67	5.856
CH	52_2	54	0.020	45.42	0.040	60	0.022	0.33	0.0002	0.274	4.136
CH	52_3	42	0.016	39.53	0.039	48	0.019	2.12	0.0017	0.492	4.796
NE	6_1	47	0.044	18.55	0.021	42	0.039	2.34	0.0023	0.476	4.064
NE	6_2	27	0.021	17.93	0.012	40	0.031	1.19	0.0008	0.228	1.686
NE	6_3	42	0.021	19.33	0.010	36	0.018	1.97	0.0010	0.61	4.36
NCC	7_1	10	0.009	23.71	0.015	6	0.006	0.72	0.0004	0.474	5.724

NCC	7_2	9	0.007	43.97	0.024	15	0.012	1.23	0.0006	0.236	3.924
NCC	7_3	19	0.011	19.92	0.010	23	0.013	1.1	0.0005	0.484	5.38
NCC	9_1	128	0.027	17.11	0.054	117	0.025	2.86	0.0067	0.448	3.308
NCC	9_2	124	0.026	18.28	0.041	228	0.050	4.44	0.0076	0.68	4.434
NCC	9_3	122	0.026	18.83	0.040	227	0.051	5.08	0.0081	0.776	4.96
Mean±SE		**54±37[a]**	**0.018 ±0.01**	**23.74[c] ±21.35**	**0.03 ±0.02**	**95.32±57.73[b]**	**0.035 ±0.02**	**3.01±2.19[d]**	**0.005 ±0.005**	**0.89 ± 0.41**	**6.43 ± 2.42**

*****Estimations were calculated basing on dbh and tree height recorded in 2005, and wood density data.

[a, b] indicates significant difference of number of trees between recruited stems and dead stems ($p < 0.001$).

[c, d] indicates significant difference of AGB between recruited stems and dead stems ($p < 0.05$).

Ecoregions: NW: Northwest; NC: North Central Coast; NE: Northeast; CH: Central Highlands; SE: Southeast: SW: Southwest; RR: Red River Delta; SC: South Central Coast

APPENDIX IV. Complexity parameter (cp) plots and tables of G increment model and AGB increment model.

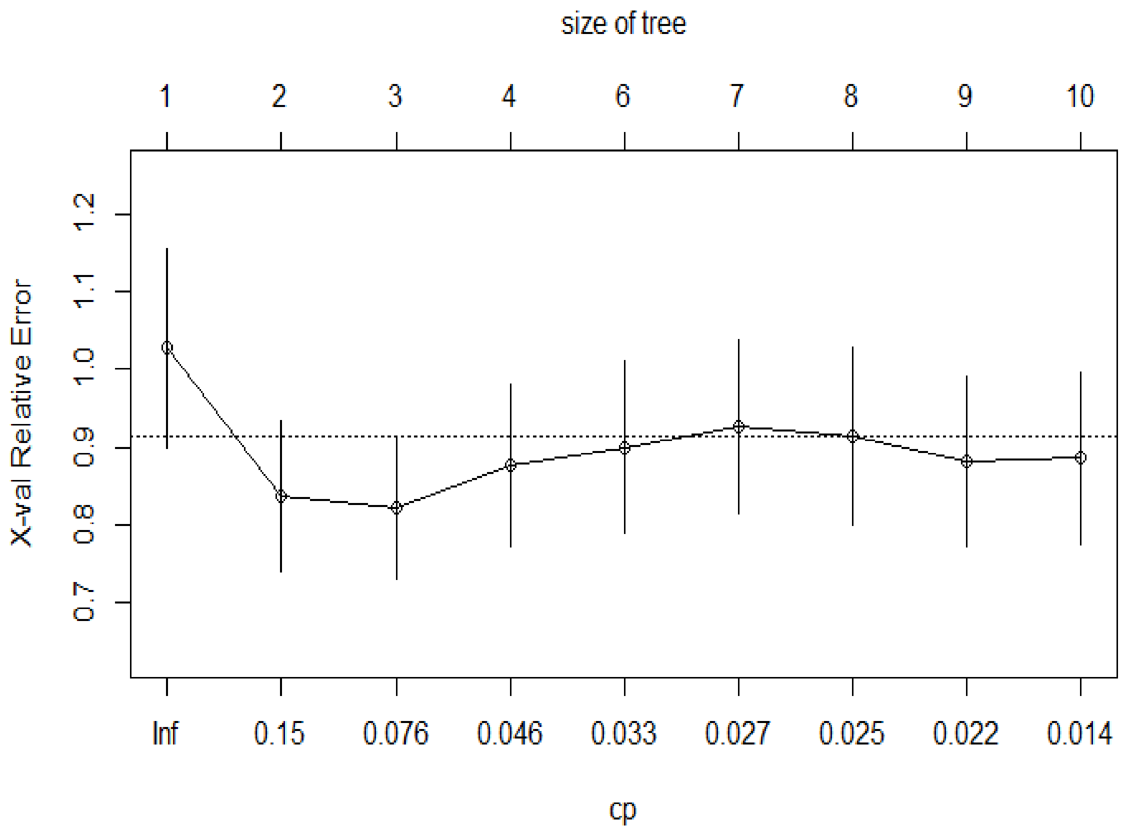

Figure 4.10. A plot of cp table for the Rpart fit to select number of tree for G increment model. The upper horizontal axis is the size of the tree. The lower axis is the complexity parameter. The vertical axis is the 10-fold cross validation.

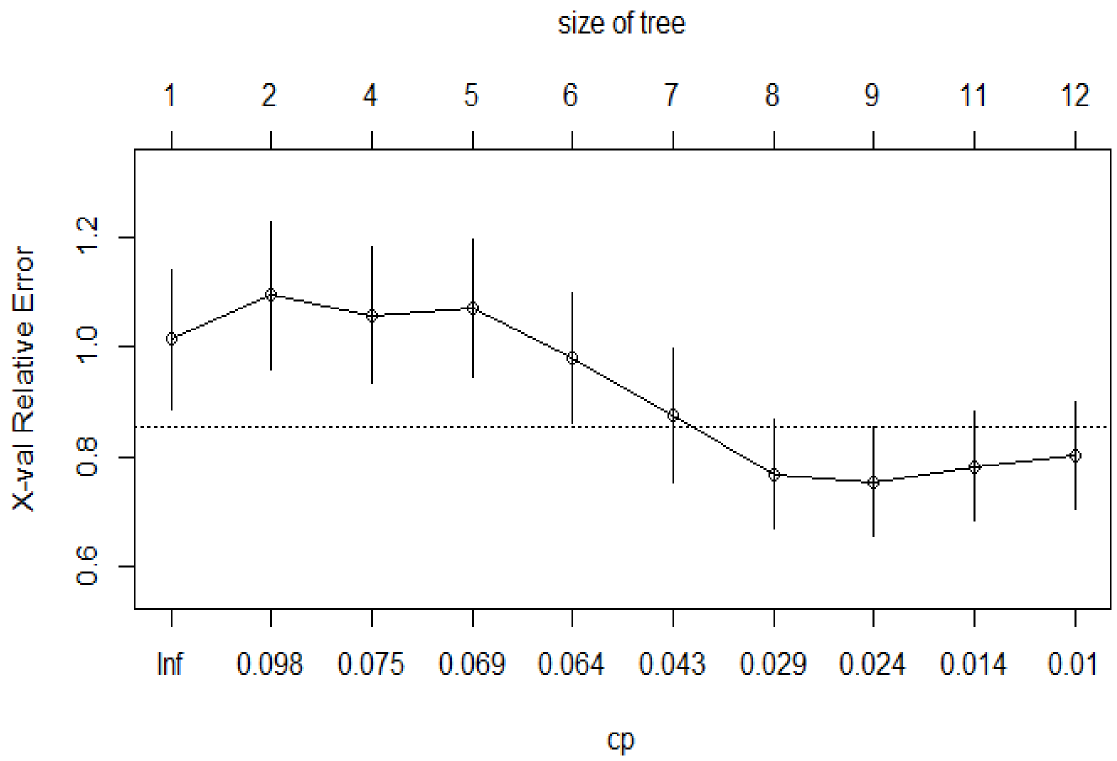

Figure 4.11. A plot of cp table for the Rpart fit to select number of tree for AGB increment model. The upper horizontal axis is the size of the tree. The lower axis is the complexity parameter. The vertical axis is the 10-fold cross validation.

Table 4.4. Number of splits, corresponding relative model error (relerror) and error estimated from a 10-fold cross validation (xerror), and the standard error of the xerror (xstd) for the Rpart fit to select number of tree for G increment model.

Complexity parameter	Number of splits	relerror	xerror	xstd
0.214297	0	1.00000	1.02724	0.127811
0.098908	1	0.78570	0.83685	0.096555
0.057782	2	0.68679	0.82224	0.092331
0.036430	3	0.62901	0.87677	0.104841
0.029298	**5**	**0.55615**	**0.89937**	**0.110126**
0.025743	6	0.52685	0.92610	0.111884
0.024603	7	0.50111	0.91386	0.114200
0.020293	8	0.47651	0.88092	0.109671
0.010000	9	0.45621	0.88603	0.110006

Table 4.5. Number of splits, corresponding relative model error (relerror) and error estimated from a 10-fold cross validation (xerror), and the standard error of the xerror (xstd) for the Rpart fit to select number of tree for AGB increment model.

Complexity parameter	Number of splits	relerror	xerror	xstd
0.124241	0	1.00000	1.00999	0.12862
0.077895	1	0.87576	1.05170	0.12541
0.071342	3	0.71997	1.12621	0.13013
0.067514	4	0.64863	1.10538	0.13071
0.060601	5	0.58111	1.06006	0.12928
0.030550	**6**	**0.52051**	**1.00622**	**0.13376**
0.028347	7	0.48996	0.95320	0.13428
0.019973	8	0.46161	0.95496	0.12240
0.010312	10	0.42167	0.95392	0.11731
0.010000	11	0.41136	0.97738	0.11976

APPENDIX V. Summary of validation data and the information of environmental indicators.

Region	plot	2007 No. Stems (tree/ha)	2007 dbh (cm; ±SE)	2007 G (m^2/ha)	2007 AGB (ton/ha)	2012 No. Stems (tree/ha)	2012 dbh (cm; ±SE)	2012 G (m^2/ha)	2012 AGB (ton/ha)	Increment G (m^2/ha/year)	Increment AGB (ton/ha/year)	Rain (mm/ year)	Solar radiation (MJ m^{-2} day^{-1})	Sand content (%)	Clay content (%)	Silk content (%)	Elev (m)
SCC	**AN1**	713	22.76(±13.76)	39.6	269.91	739	24.23(±13.53)	42.56	290.64	0.592	4.146	2327	18.558	33	40	36	108
SCC	AN2	648	19.98(±9.36)	24.76	152.45	702	19.74(±9.41)	26.36	170.36	0.32	3.582	2298	18.401	31	38	36	204
SCC	AN3	454	24(±14.02)	27.53	190.86	571	21.71(±13.61)	29.44	204	0.382	2.628	2315	18.382	29	41	36	200
NCC	DR1	623	24.76(±16.08)	42.63	289.72	684	25.55(±15.89)	47.12	302.73	0.898	2.602	2083	17.868	27	49	31	230
NCC	DR2	814	21.45(±11.8)	38.31	247.48	833	22.36(±11.41)	42.36	262.13	0.81	2.93	2262	18.065	31	51	31	269
NCC	DR3	638	24.83(±13.31)	39.74	266.36	653	25.7(±13.42)	43.19	288.12	0.69	4.352	2202	18.103	33	50	32	864
NCC	DR4	942	20.83(±10.13)	39.7	254.3	956	21.98(±10.39)	44.5	272.85	0.96	3.71	2156	17.565	28	48	37	864
NCC	DR5	557	24.53(±14.76)	35.84	246.92	568	25.22(±14.92)	39.54	277.92	0.74	6.2	2183	17.860	32	46	36	864
NCC	DR6	549	24.11(±14.64)	34.3	233.07	549	25.2(±15.02)	37.09	254.14	0.558	4.214	2170	17.675	29	47	37	864
NW	HB1	561	19.86(±10.58)	22.3	143.27	583	20.33(±11.10)	25.5	177.44	0.64	6.834	2381	14.791	31	39	36	364
NW	HB2	507	20.81(±9.88)	21.13	130.7	525	21.69(±10.46)	23.65	144.63	0.504	2.786	2350	14.696	29	35	34	764
NW	HB3	509	18.13(±8.29)	15.89	97.79	560	18.82(±8.56)	20.18	118.74	0.858	4.19	2368	14.697	30	37	35	786
NW	HB4	614	16.95(±8.16)	17.05	99.71	634	18.72(±9.13)	21.11	127.3	0.812	5.518	1995	14.597	32	39	36	986
NW	HB5	458	21.45(±12.07)	21.78	172.7	464	22.28(±13.3)	24.05	190.96	0.454	3.652	1968	15.085	33	41	38	173
NW	HB6	440	25.83(±15.77)	31.64	255.39	462	26.17(±16.49)	34.95	275.49	0.662	4.02	1945	14.821	32	37	36	771
NCC	HT1	260	22.58(±10.64)	12.72	81.98	283	23.05(±11.26)	14.77	105.98	0.41	4.8	2309	14.286	33	42	34	675
NCC	HT2	319	17.98(±8.85)	10.05	64.39	345	18.44(±9.79)	14.03	101.42	0.796	7.406	2279	14.780	34	44	34	90
NCC	HT3	312	25.13(±14.89)	20.89	143.97	334	24.64(±15.41)	22.98	158.98	0.418	3.002	1857	14.769	34	40	34	83
NCC	HT4	416	25.31(±16.40)	29.69	192.49	428	26.09(±14.66)	34.05	215.06	0.872	4.514	1977	15.745	35	37	34	83
NCC	HT5	326	27.02(±15.61)	24.91	166.14	354	28.22(±14.88)	27.32	182.62	0.482	3.296	1548	15.625	31	47	35	48
NCC	HT6	302	28.19(±17.84)	26.37	206.2	334	29.32(±17.99)	28.97	223.5	0.52	3.46	1513	14.773	29	43	34	1140
CH	KHN1	380	24.42(±14.01)	23.65	174.05	390	24.95(±13.57)	27.25	195.5	0.72	4.29	1596	15.800	34	46	33	1242
CH	KHN10	583	22.44(±13.55)	31.45	225.56	582	23.26(±14.40)	34.2	249.11	0.55	4.71	2317	18.251	30	39	34	1040

CH	KHN2	521	25.39(±16.51)	37.51	333.55	514	26.25(±17.18)	39.72	356.56	0.442	4.602	2412	18.264	33	42	34	1140
CH	KHN3	405	23.77(±13.33)	23.61	169.2	423	24.52(±13.92)	26.39	191.43	0.556	4.446	1930	18.450	33	38	35	940
CH	KHN4	469	22.28(±13.23)	24.72	175.8	494	22.97(±13.32)	27.34	195.71	0.524	3.982	1830	18.332	32	39	35	290
CH	KHN5	633	21.63(±12.86)	31.46	236.93	626	22.569(±13.29)	33.69	265.33	0.446	5.68	1790	18.361	34	36	35	403
CH	KHN6	413	25.83(±17.71)	31.79	267.78	445	25.85(±18.15)	34.83	292.23	0.608	4.89	1738	17.800	34	39	34	315
CH	KHN7	592	22.6(±12.88)	31.45	232.29	611	23.46(±13.5)	35.15	263.32	0.74	6.206	1769	17.526	29	39	34	231
CH	KHN8	513	24.8(±18.29)	38.24	297.11	525	25.5(±19.1)	41.81	328.06	0.714	6.19	1638	18.535	30	44	34	239
CH	KHN9	511	23.52(±16.08)	32.55	241.98	516	24.54(±16.98)	36.07	271.17	0.704	5.838	1690	18.522	29	47	35	262
RRD	XS1	394	29.2(±16.56)	26.01	184.29	422	28.85(±16.14)	29.32	205.31	0.662	4.204	1685	17.530	31	54	37	670
RRD	XS2	344	25.26(±13.49)	19.57	148.82	361	26.65(13.54)	21.11	161.35	0.308	2.506	1536	14.269	31	53	34	540
RRD	XS3	446	23.84(±14.74)	27.5	213.43	455	23.72(±14.69)	31.12	237.84	0.724	4.882	1683	14.600	34.5	48	32	563

Ecoregions: NW: Northwest; NC: North Central Coast; NE: Northeast; CH: Central Highlands; SE: Southeast: SW: Southwest; RR: Red River Delta; SC: South Central Coast